

# **- Compositional Evolution of interstellar Gas in Galaxies -**

**NOAJ Astrophysics Lecture Series, November 2013**

**Introduction to Observational Nuclear Astrophysics  
Lecture #6**

**by Roland Diehl**

# Cosmic Conversion of Gas to Stars

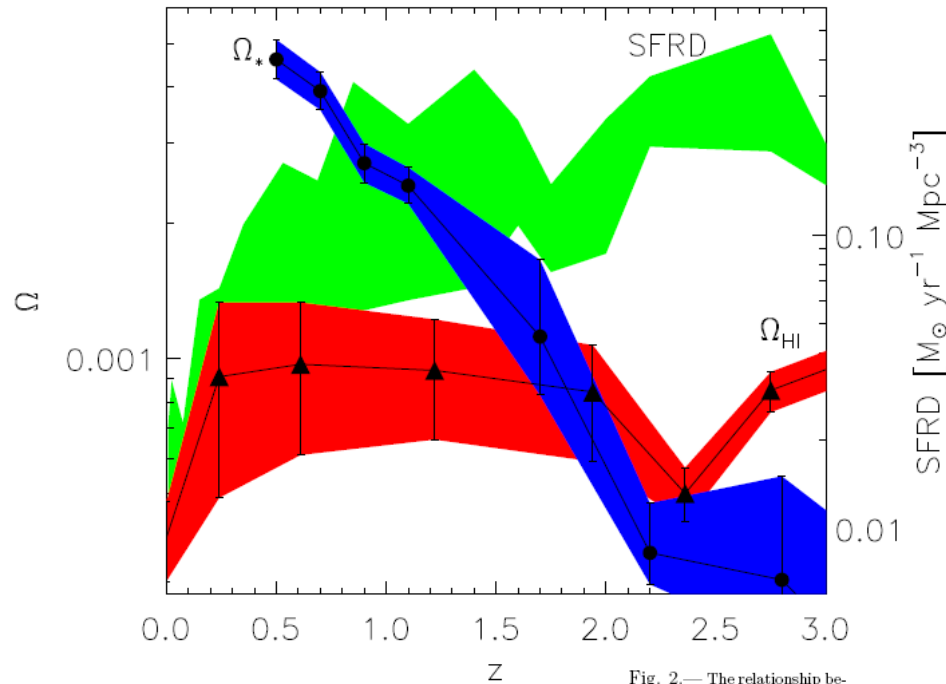


Fig. 2.— The relationship between the mass density in stars,  $\Omega_{\text{stars}}$  (blue<sup>78,79</sup>), and in gas,  $\Omega_{\text{HI}}$  (red<sup>33,75,80,81</sup>) as a function of redshift. The shaded regions show estimates of the error on these values. For  $\Omega_{\text{HI}}$  the points above  $z = 0.24$  are determined from absorption line studies. Also shown is the range of star formation rate density of galaxies as a function of redshift (green<sup>82</sup>).

★ Today, a Substantial Fraction of Baryonic Matter is in Stars

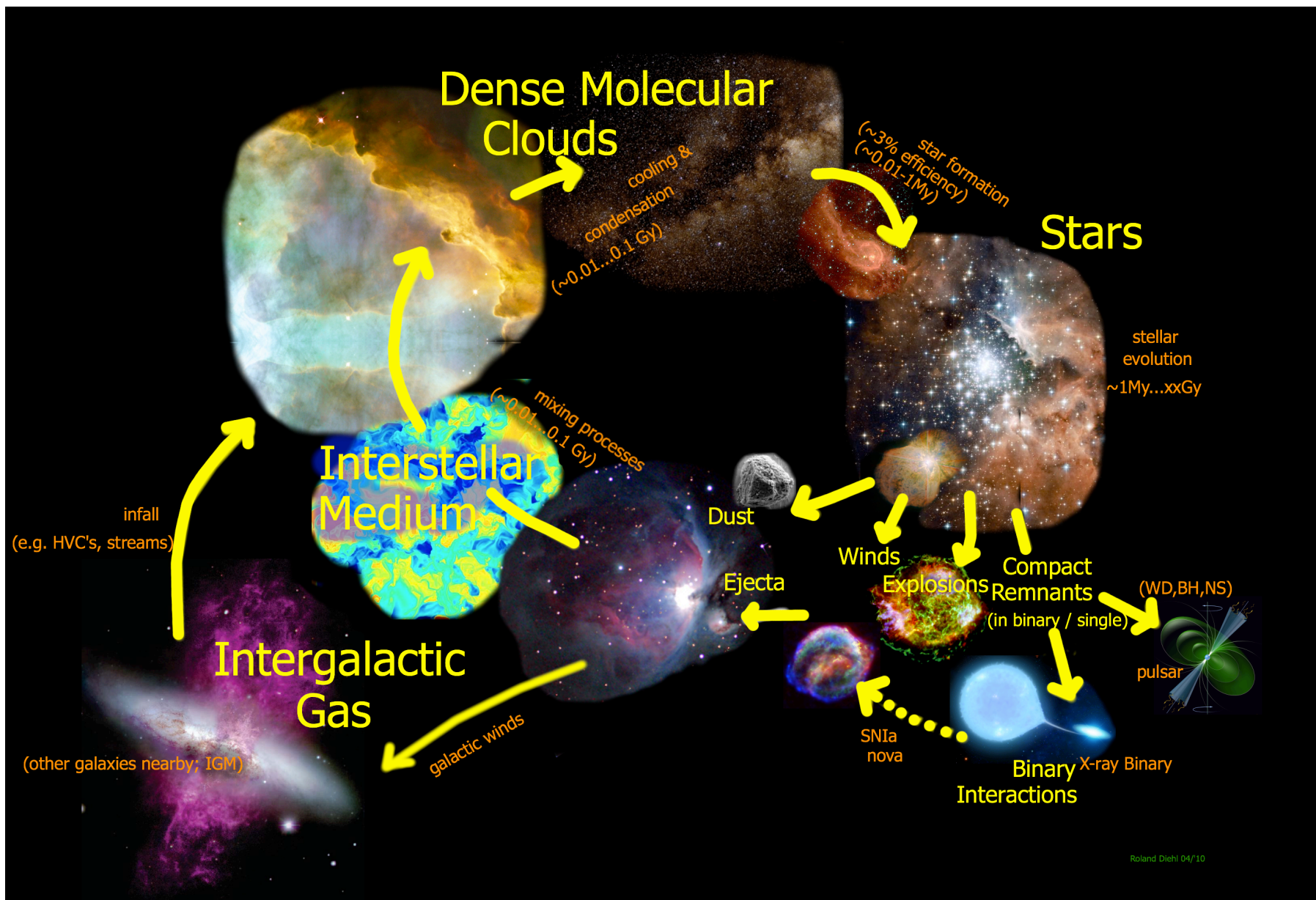
★ The Star Formation Rate Varies Significantly with Cosmic Epoch and with Environment

★ The Cosmic Census of Interstellar Gas is Incomplete

★ Uncertainties on these Measures of Cosmic Evolution are Large

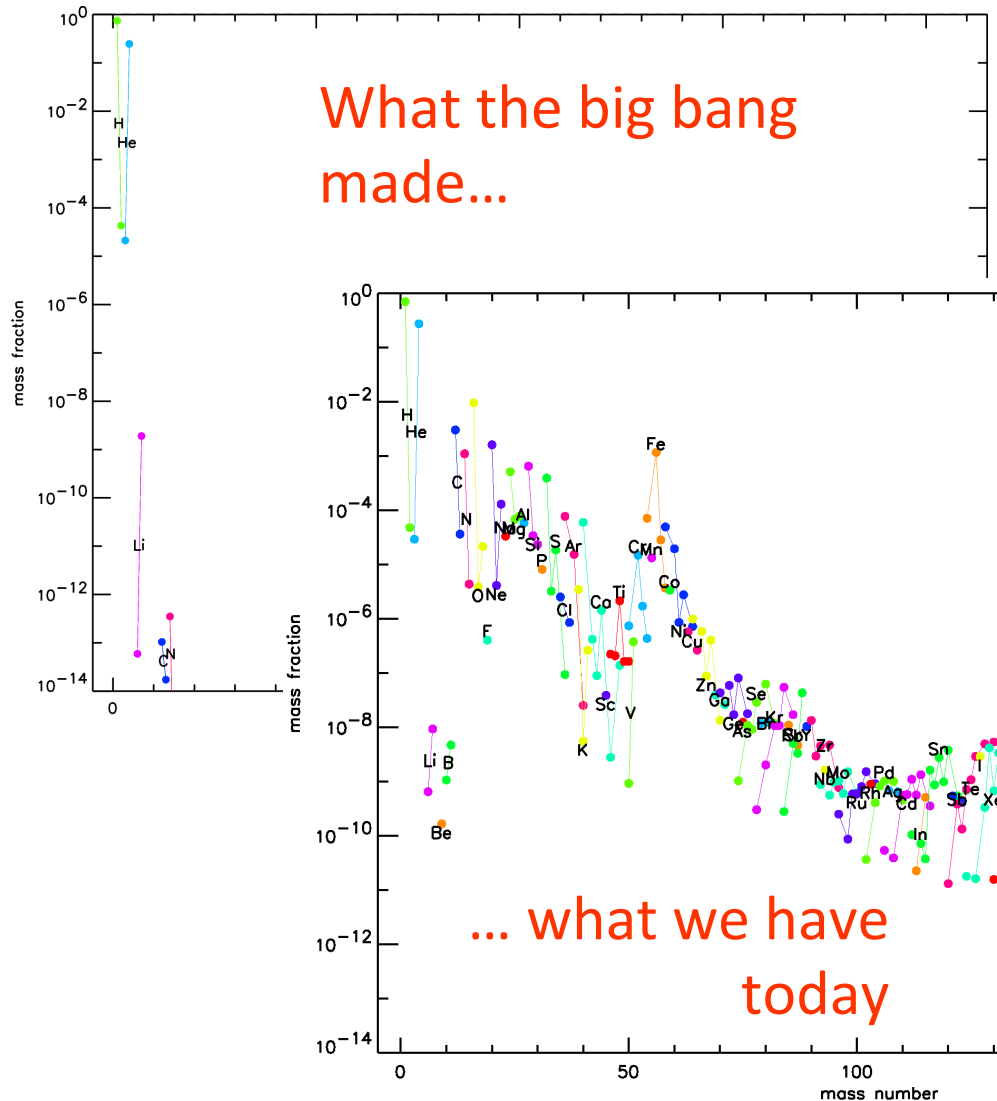


# Cycling of Matter: ISM through Stars

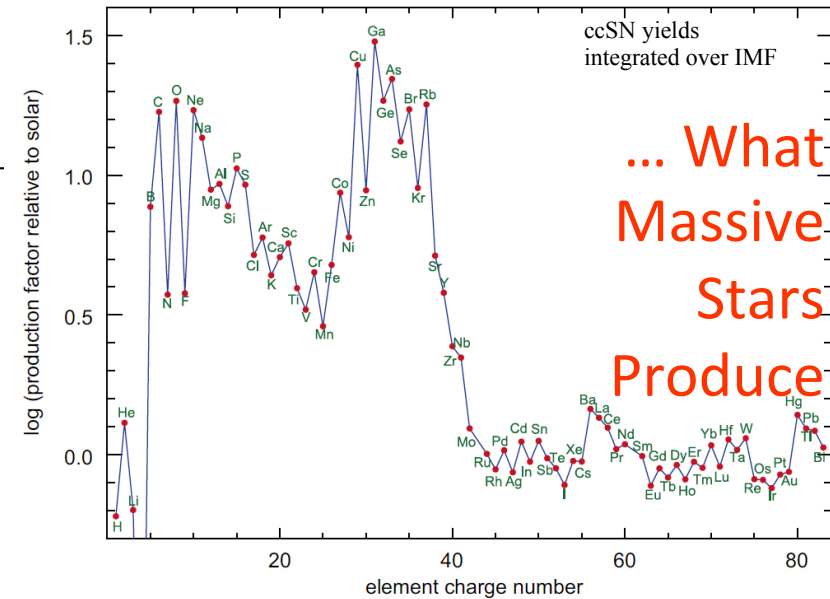


Roland Diehl 04/10

# Compositional Evolution of the Universe



courtesy Alex Heeger  
S.E. Woosley, A. Heger / Physics Reports 442 (2007) 269–283



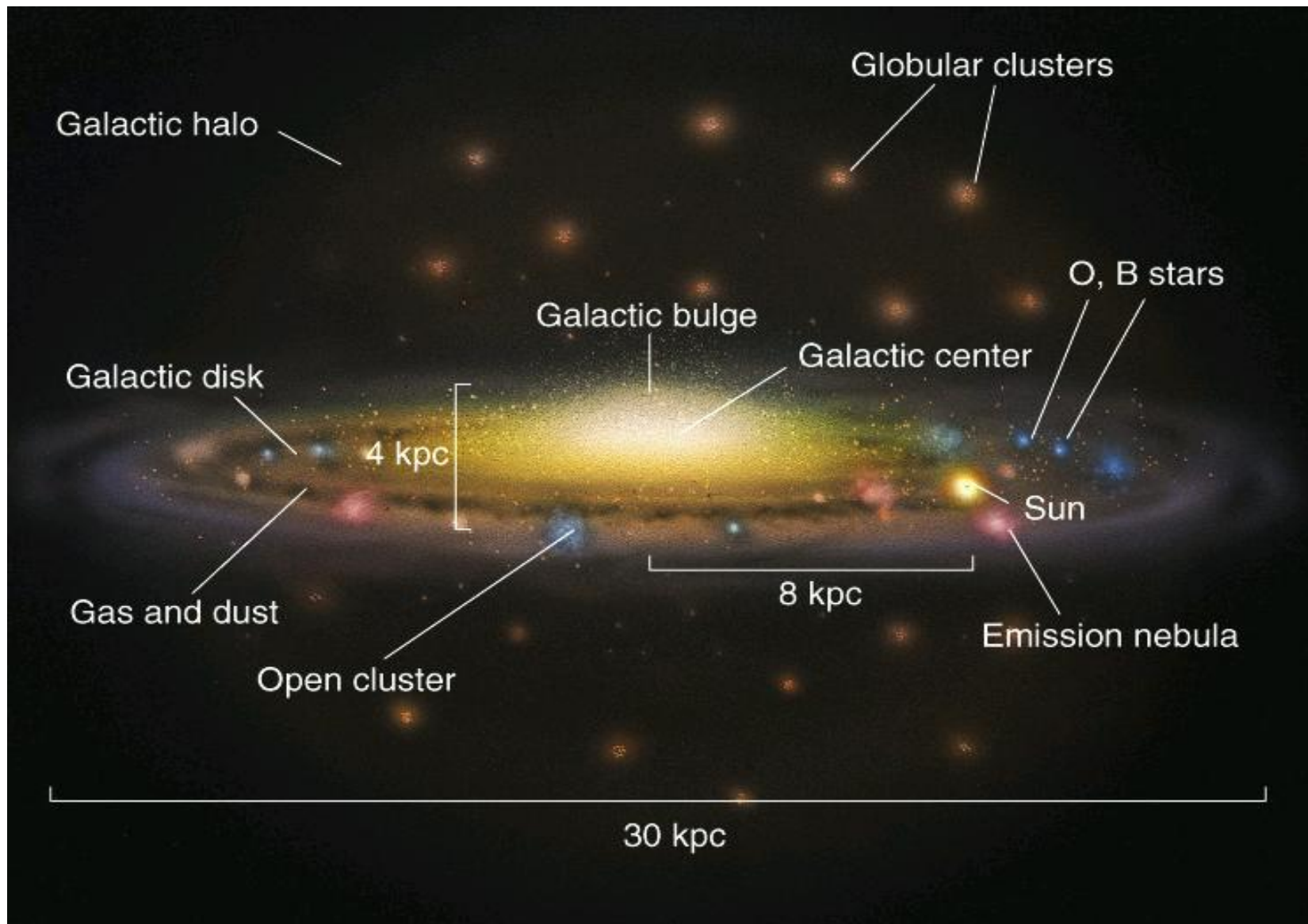
# The Interstellar Medium

- **ISM as a Key Component of Galaxies**
  - Galaxy Components and Objects
  - Flows of Energy and Matter
- **ISM Details**
  - ISM Phases, Evolution
  - Star/ISM Interactions
- **High-Energy Phenomena**
  - Hot Plasma
  - Cosmic Rays
  - New Nuclei

# Questions addressed in this lecture

- ★ How the ISM in Galaxies Appears  
(& Galaxies, Galactic Structure)
- ★ Observables of the ISM (emphasis: HE-Emissions)
- ★ How we understand the ISM
- ★ Why it is important for astrophysics to understand the ISM
- ★ The ISM and its Relation to Energy Sources in the Galaxy
- ★ The ISM and diffuse gamma-rays from nuclear reactions

# Galaxy Constituents





# The Interstellar Medium

- **Masses**

★ Galaxy total / ISM total / ISM gas:  
 $1 \cdot 10^{12} M_{\odot}$  /  $1.4 \cdot 10^{11} M_{\odot}$  /  $4 \cdot 10^9 M_{\odot}$

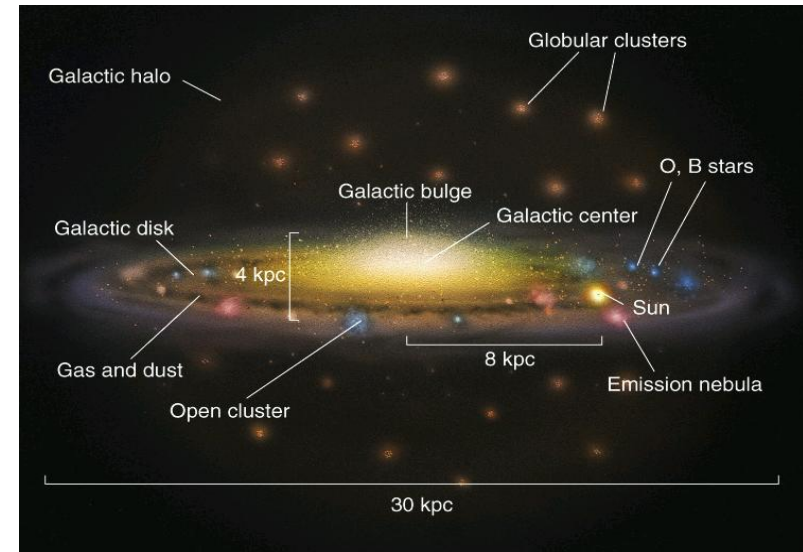
- **Gas Components**

★ **Diffuse ISM**

- ☞ Hot Gas ( $T > 10^6 \text{K}$ ; plasma)
- ☞ Warm Ionized Gas ( $T \sim 10^4 \text{K}$ ;  $e^-$ , ions)
- ☞ Cold Gas ( $T \sim 10\text{-}100 \text{K}$ ; neutral)
- ☞ Dust
- ☞ Cosmic Rays

★ **Clouds & Prominent Regions**

- ☞ Diffuse Clouds
- ☞ Molecular Clouds
  - Giant Molecular Clouds (GMC)
  - Dark Clouds
- ☞ HII Regions
- ☞ SNR, Superbubbles



★ Nomenclature: “HI”

★ E.M.Radiation from  
H Transition = Hyperfine-Structure ( $e^-$  spin transition)

👉 Line at 1420.4 MHz = 21.1 cm

$$\tau_{\text{collision}} \ll \tau_{\text{transition}}$$

👉 Thermal Population

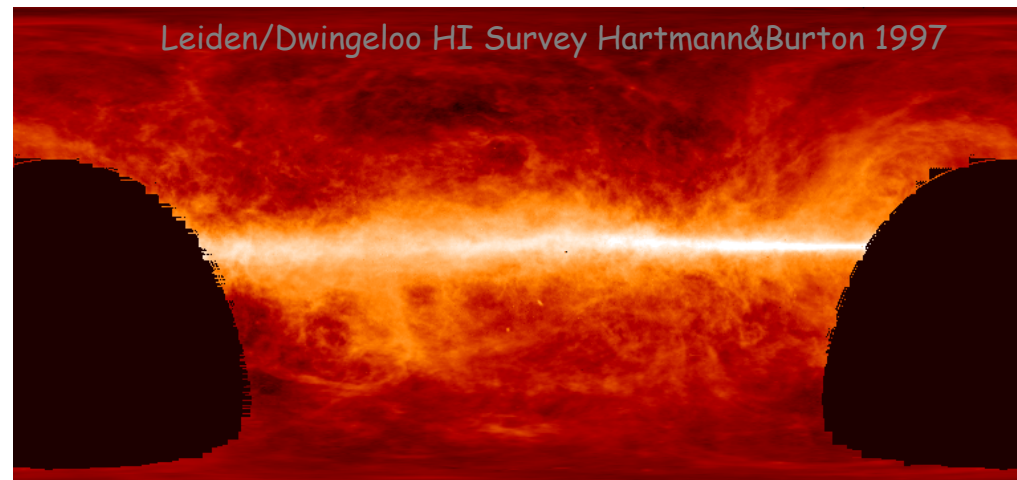
$$\frac{h\nu}{k_B} = 7 \cdot 10^{-2} \text{ K} \ll T_{\text{gas}} \rightarrow \frac{N_2}{N_1} = 3$$

» known level populations

$$I = \frac{3}{16\pi} Ah\nu_0 \int N_H dl$$

👉 Intensity → Measurement of  
Total Column Density

👉 Velocity → Estimate of Distance  
(using velocity curve)



# Molecular Gas

## ★ Radiation from

- ☞ Electronic Transitions  $\sim 2 \text{ eV}$
- ☞ Vibrational Transitions  $\sim 0.2 \text{ eV}$
- ☞ Rotational Transitions  $10^{-16} \text{ eV}$

optical

NIR

Radio

## ★ Optical Depth $\tau_{\text{radio}} \ll \tau_{\text{optical}}$ (from dust absorption)

☞ Mostly Radio Measurements

$$\nu = \frac{j\hbar}{2\pi\mu r_0^2}$$

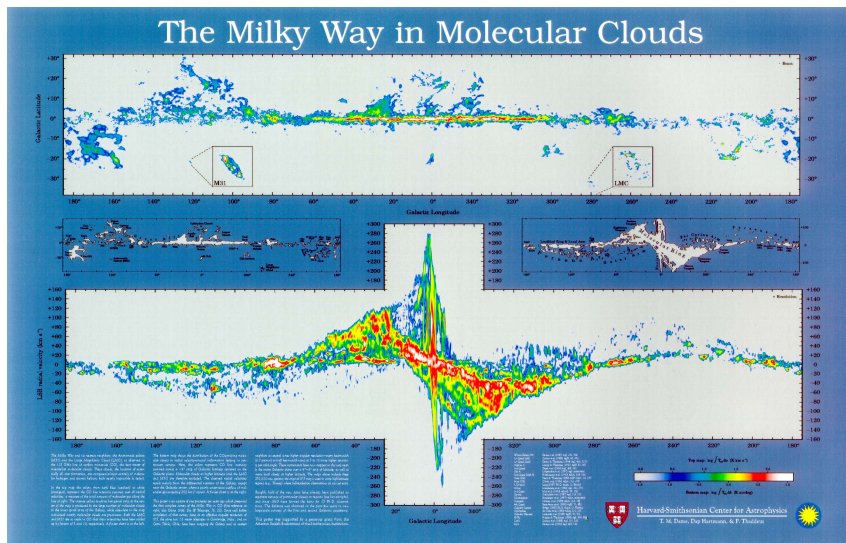


» e.g.: CO  $m=6.859 \text{ amu}$ ,  $r_0=1.128 \cdot 10^{-8} \text{ cm}$ ,

rotational transitions =>

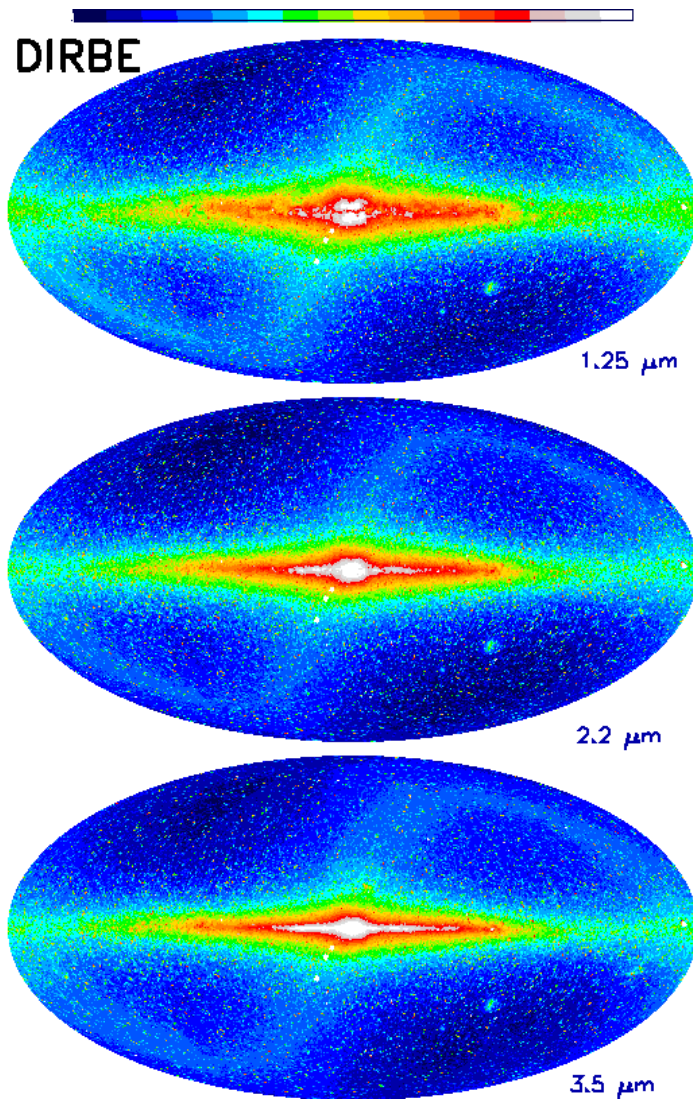
$j=1 \rightarrow j=0$ :	115 GHz	2.61 mm
	230	1.3
	345	0.87

equidistant levels

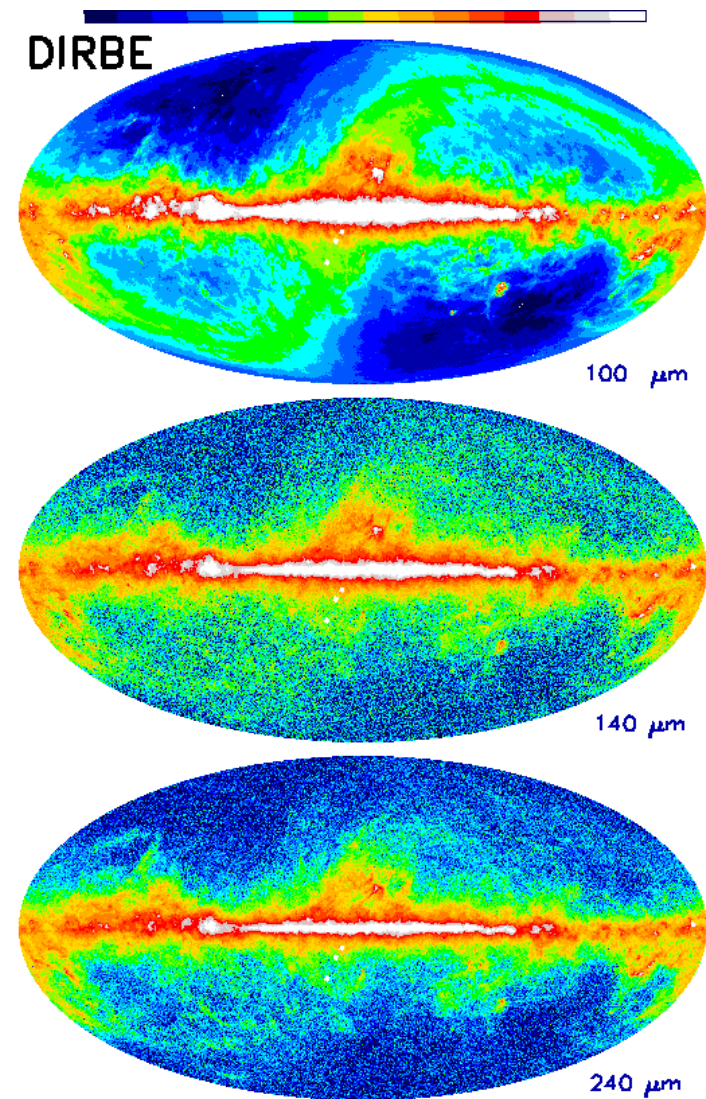




# The Infrared Galaxy



Starlight

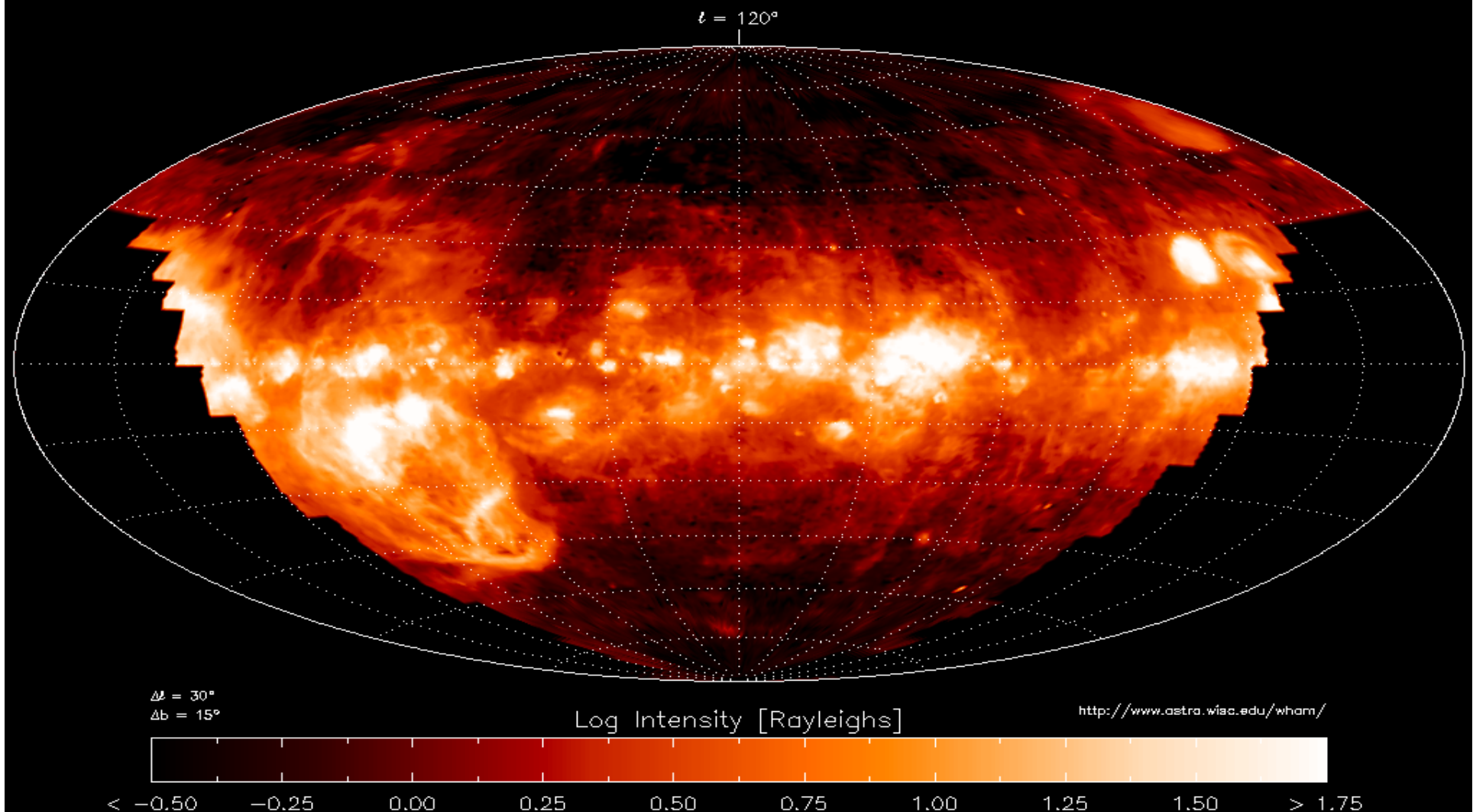


Dust Emission

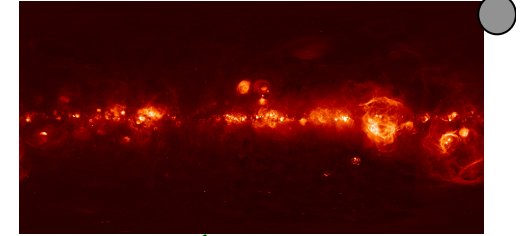
# Ionized Gas in the Galaxy



Wisconsin H-Alpha Mapper Northern Sky Survey  
Total Integrated Intensity Map ( $-80 < v_{\text{LSR}} < +80 \text{ km s}^{-1}$ )



# Ionized Gas



## ★ Recombination Transitions

» e.g. Balmer Series

or

Ha 656.3 nm  
Hb 466.1 nm  
H<sub>Brg</sub> 2.1 mm

n=1  
n=2

## ★ Ionization of Gas by Central Source (HII Regions, Planetary Nebulae)

☞ Ionization-Bounded if All Ionizing Photons  $E > E_{\text{ionization}}$  are Absorbed

☞ Density-Bounded if Limited by Central Source's Luminosity at  $E > E_{\text{ionization}}$

## ★ Ionization/Recombination Dynamic Balance: (<-conservation of atoms)

$$Q_{E>E_{\text{ionization}}} + \int n_{\text{ions}} n_e \cdot \varepsilon_{\text{volume}} \cdot A_{\text{recomb,groundlevel}}(^Z A, T) \cdot dV = \int n_{\text{ions}} n_e \cdot \varepsilon \cdot A_{\text{recomb,total}}(^Z A, T) \cdot dV$$

$$I \approx n_e \cdot n_{\text{ion}} \cdot V_{\text{eff}} \cdot A \cdot h \nu$$

☞ For H-dominated Gas in Equilibrium:

$$I = 2.28 \cdot 10^{-26} n_e^2 \cdot T^{-3/2} \cdot e^{13000/T_e}$$

$$I \propto \int n_e^2 \cdot T^{-3/2} dl$$

☞ Ionized-Region Sizes:

» Strömgren Sphere

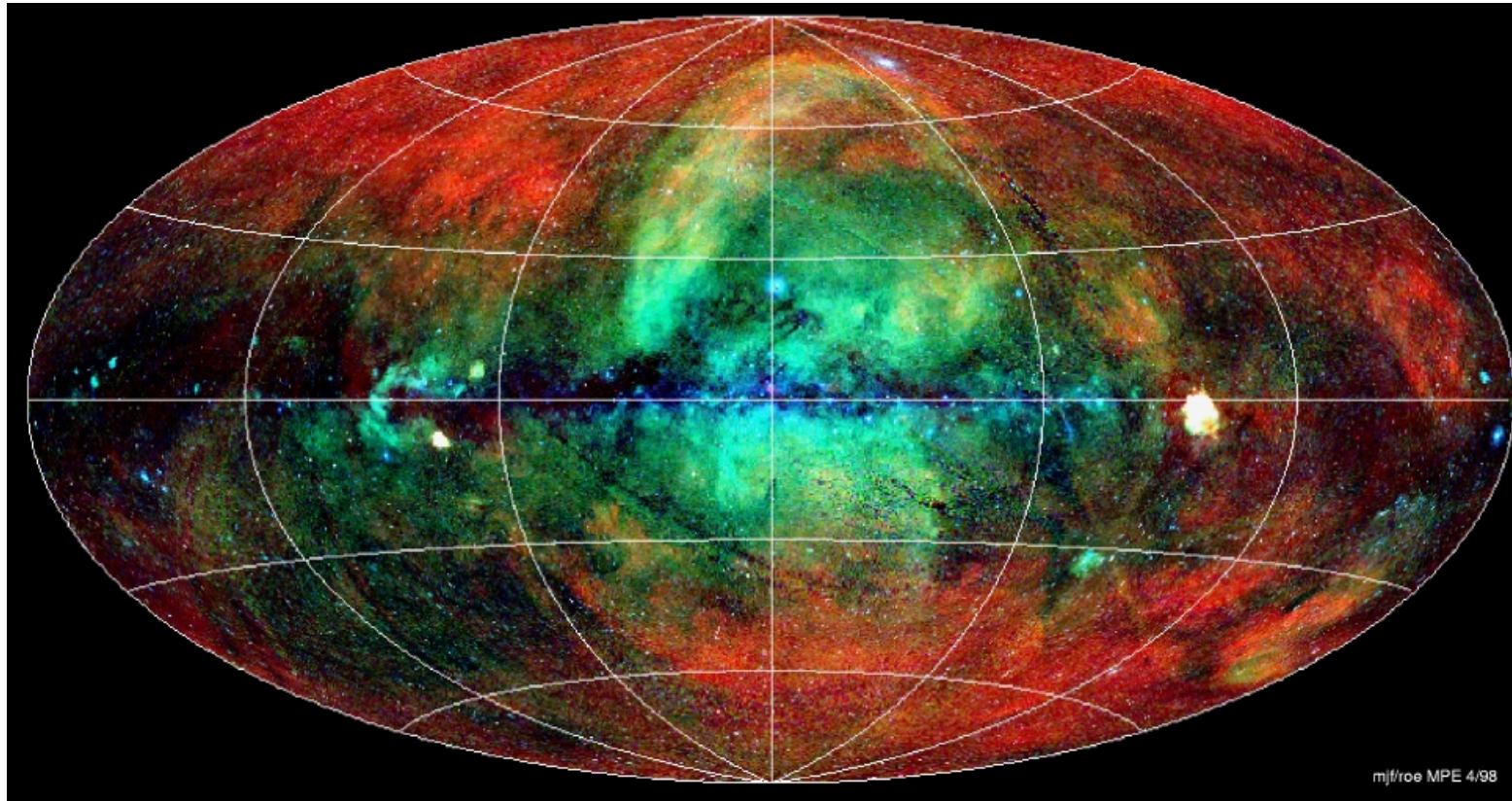
$$R_S = \left( \frac{3Q(\text{H}^0)}{4\pi e n_e^2 \alpha_B(\text{H}, T_e)} \right)^{1/3}$$

	$Q(\text{H}^0)$	$M_\star$	$M_{\text{ion}}$	$M_{\text{ion}}$
			$n = 10^2 \text{ cm}^{-3}$	$n = 10^4 \text{ cm}^{-3}$
planetary nebula	$3 \cdot 10^{47} \text{ ph s}^{-1}$	$0.6 M_\odot$	$10 M_\odot$	$10^{-1} M_\odot$
single star H II region	$3 \cdot 10^{48} \text{ ph s}^{-1}$	$30 M_\odot$	$10^2 M_\odot$	$1 M_\odot$
giant H II region	$3 \cdot 10^{50} \text{ ph s}^{-1}$	$10^4 M_\odot$	$10^4 M_\odot$	$10^2 M_\odot$



# Hot ISM: X-ray Emission

★ Hot Plasma  $\rightarrow$  X-ray Emission ( $E \sim \text{keV}$ )



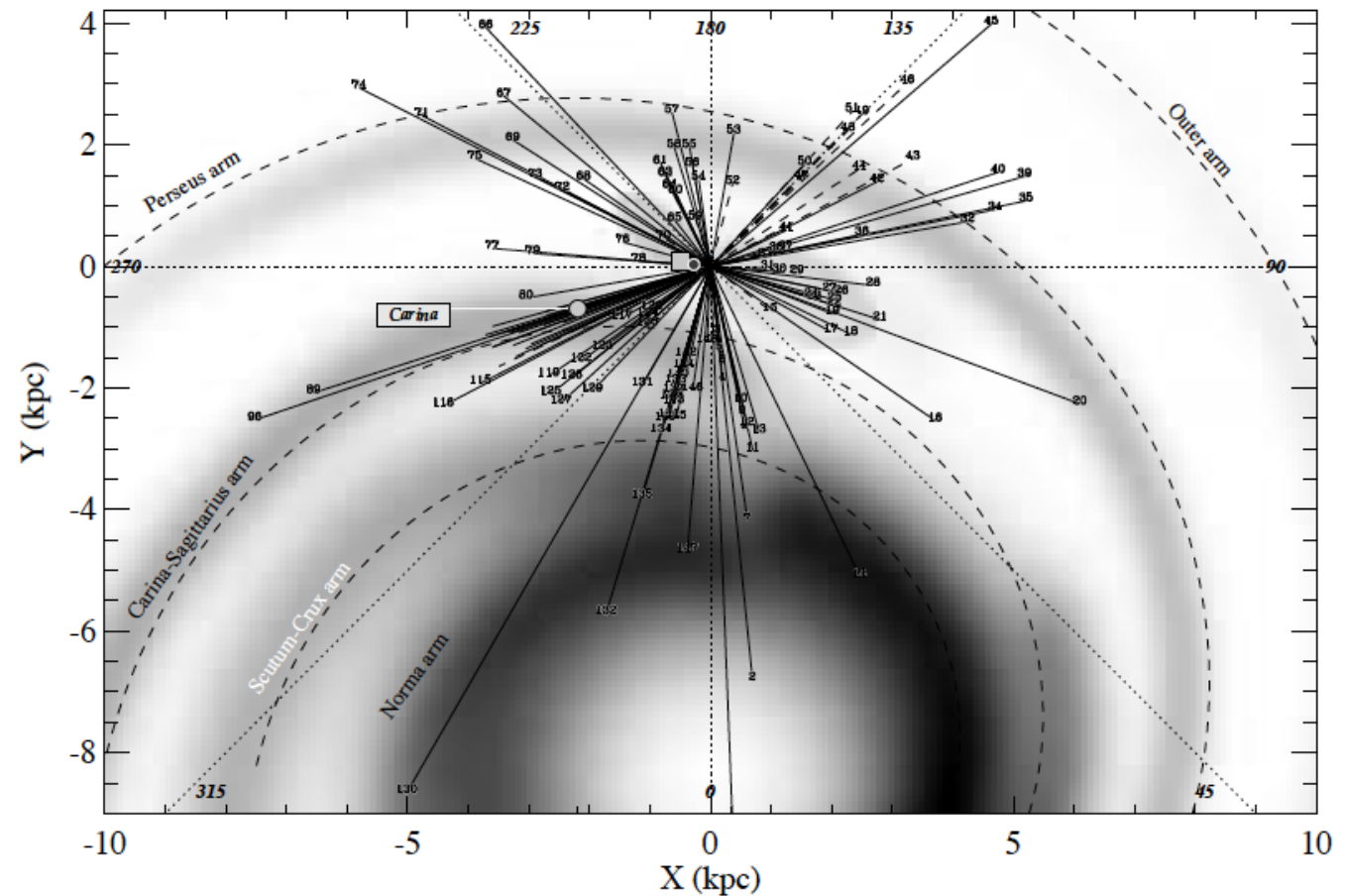
☞ Occultation by Molecular Clouds

☞ Hottest Regions: Cavities with Recent Supernova Activities

# The Hot Interstellar Medium: O VI



- Absorption lines from O VI in UV, against bgd stars  
👉 **FUSE UV measurements**



# The Hot Interstellar Medium: O VI



- Absorption lines from highly-ionized gas

- ★  $O^{4+} = O\ VI$  ionization potential  $\sim 114\ eV$

- ☞ higher than C and Si, not contaminated by cooler partially ionized gas

- ★ Line doublet 103.2 and 103.7 nm (UV)

- ★ Typical  $T_{\text{gas}} \sim 3 \cdot 10^5\ K$

- ★ Search for background stars with known distances

- ☞ Parallax, or spectroscopic;  $\sim$  few kpc

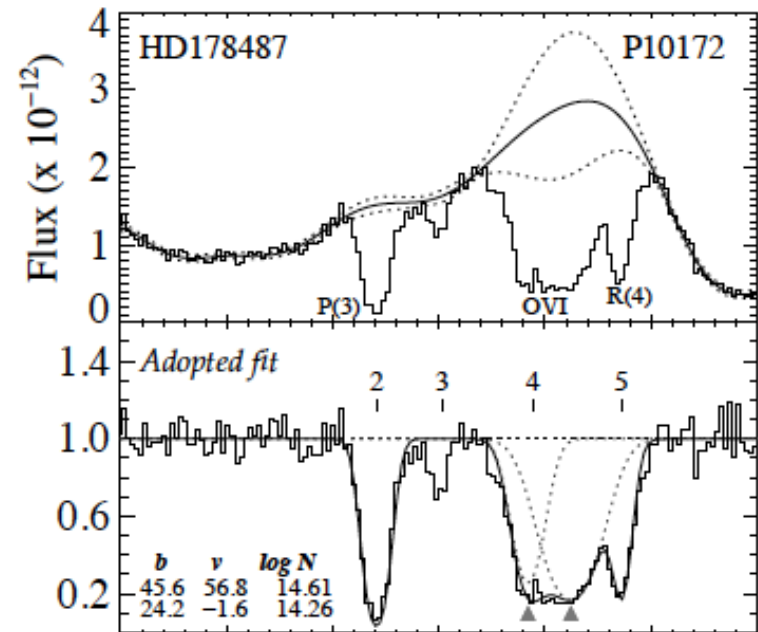
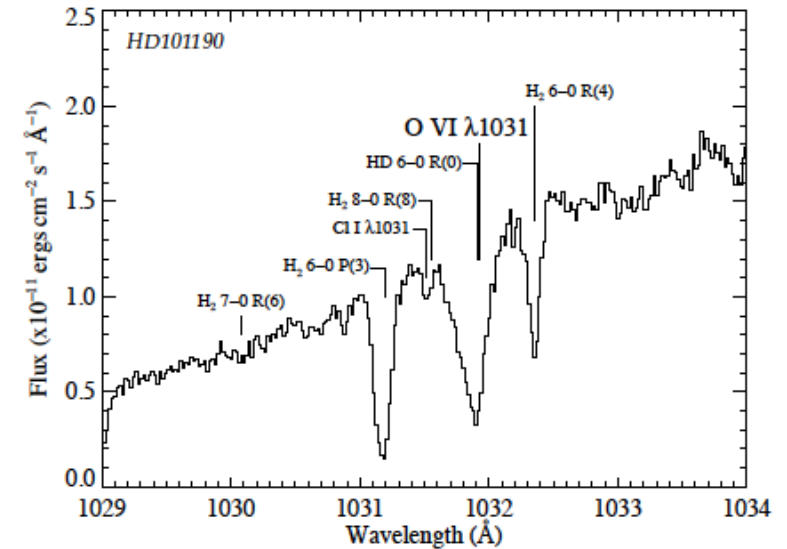
- ★ Select stars with

- ☞ low  $H_2$  absorption from foreground gas

- ★ Correct for HD absorption

- ★ Fit underlying continuum

- FUSE and Copernicus

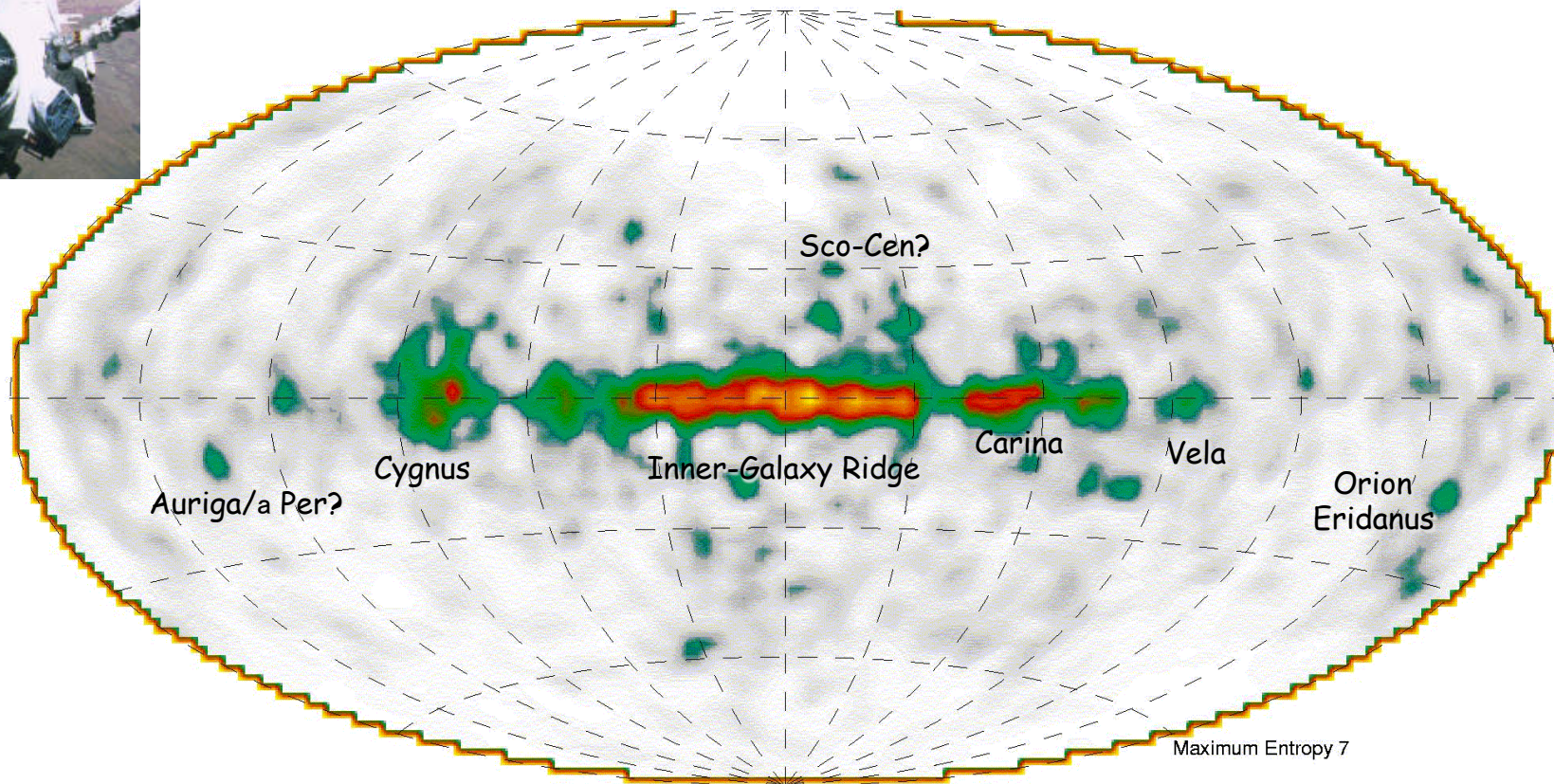




# The Sky Glows at 1809 keV: Radioactive $^{26}\text{Al}$



$1.04 \cdot 10^6 \text{ y}$	$^{26}\text{Al} \rightarrow ^{26}\text{Mg}^* + e^+$	1809
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Complete CGRO Mission (9y)  
(Plüschke et al. 2001)

Radioactive Nuclei in ISM Show the Regions of Recent Nucleosynthesis

# Rotation of Gas and Stars in Galaxies



- Non-Keplerian Rotation
  - ★ Dark Matter Builds an Extended Gravitational Potential

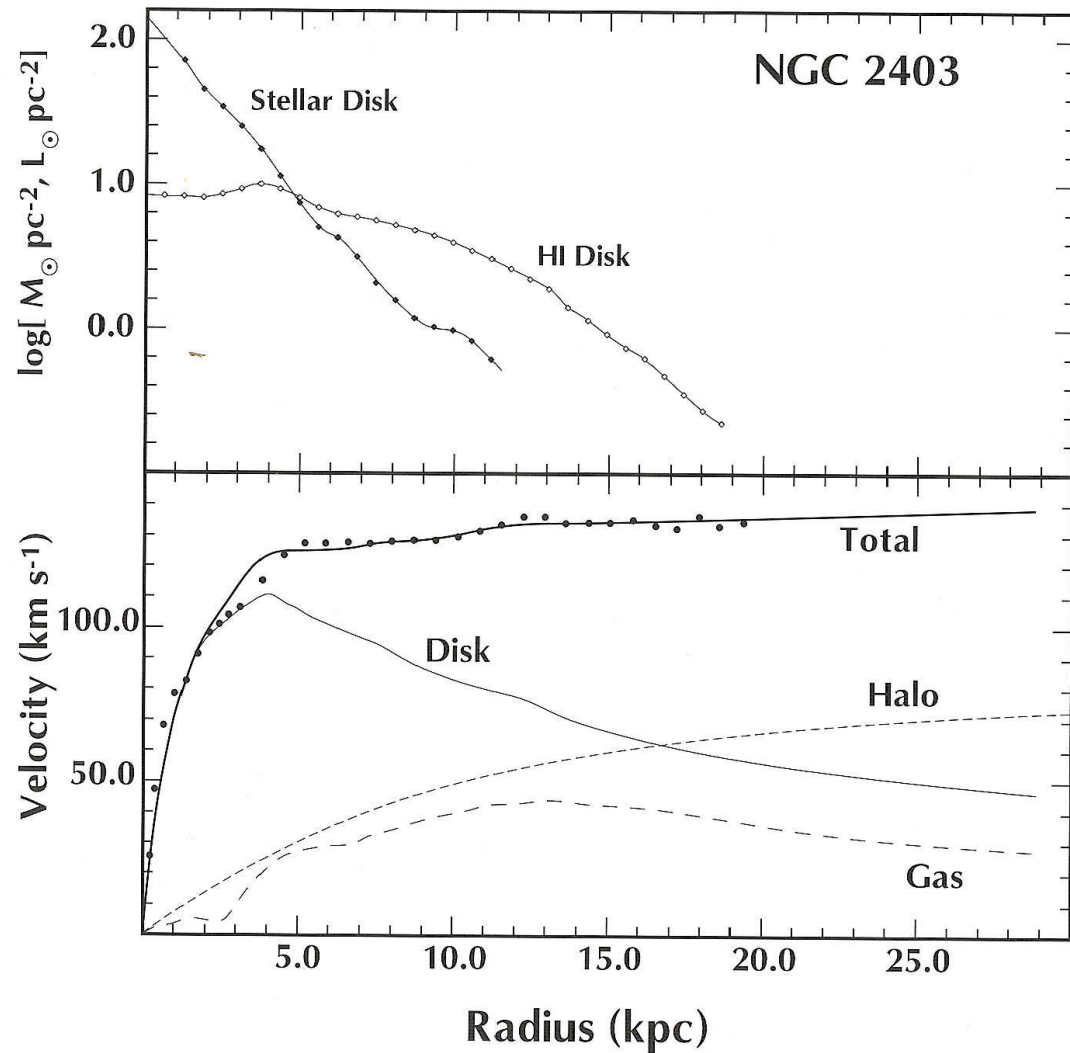
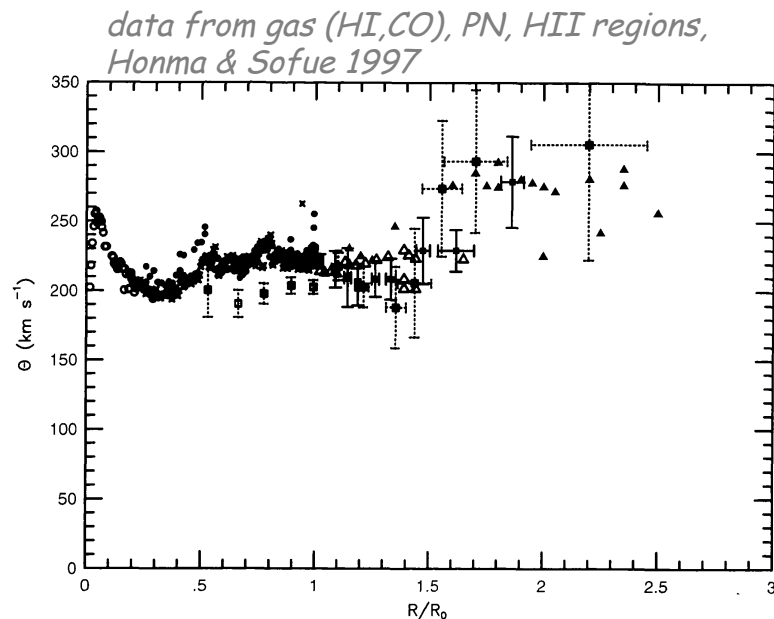
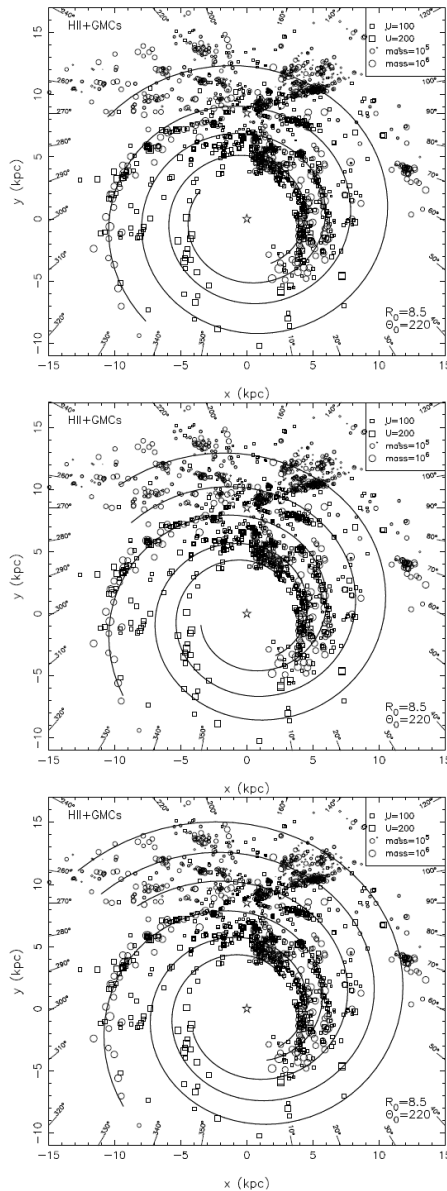


Fig. 4.8. Galactic rotation data and maximal disk fit for NGC2403 (after Begeman 1987).



# The Galaxy's Spiral Structure and Rotation



- ➡ Two-Spiral Arm Model Unlikely
- ➡ 3-4 Spiral Arms are Consistent with all Observational Constraints

➡ Best Constraints on Large-Scale Galactic Rotation are from Solar-Vicinity Stellar Kinematics

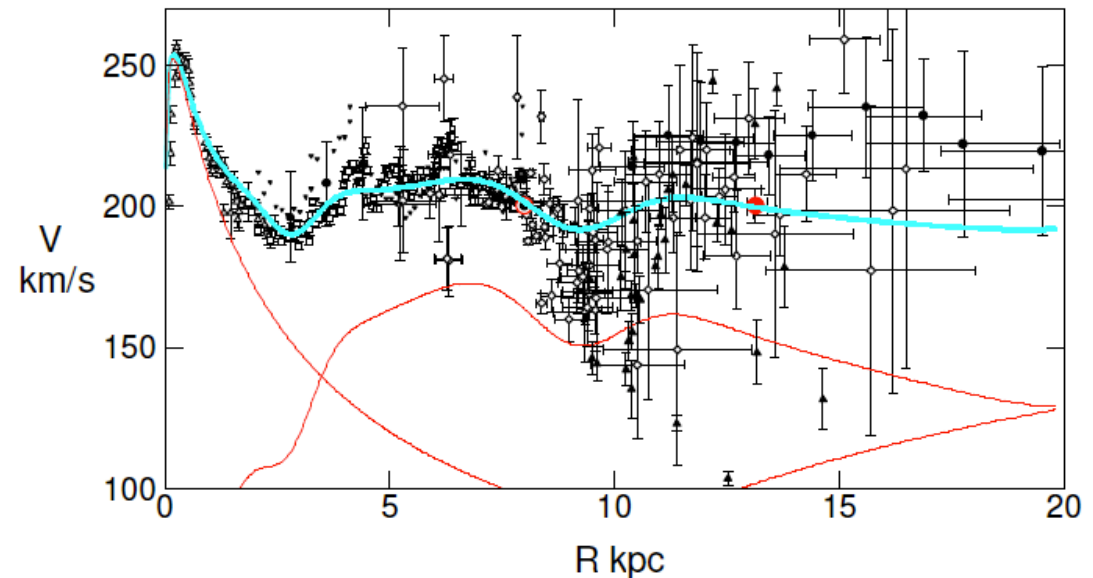
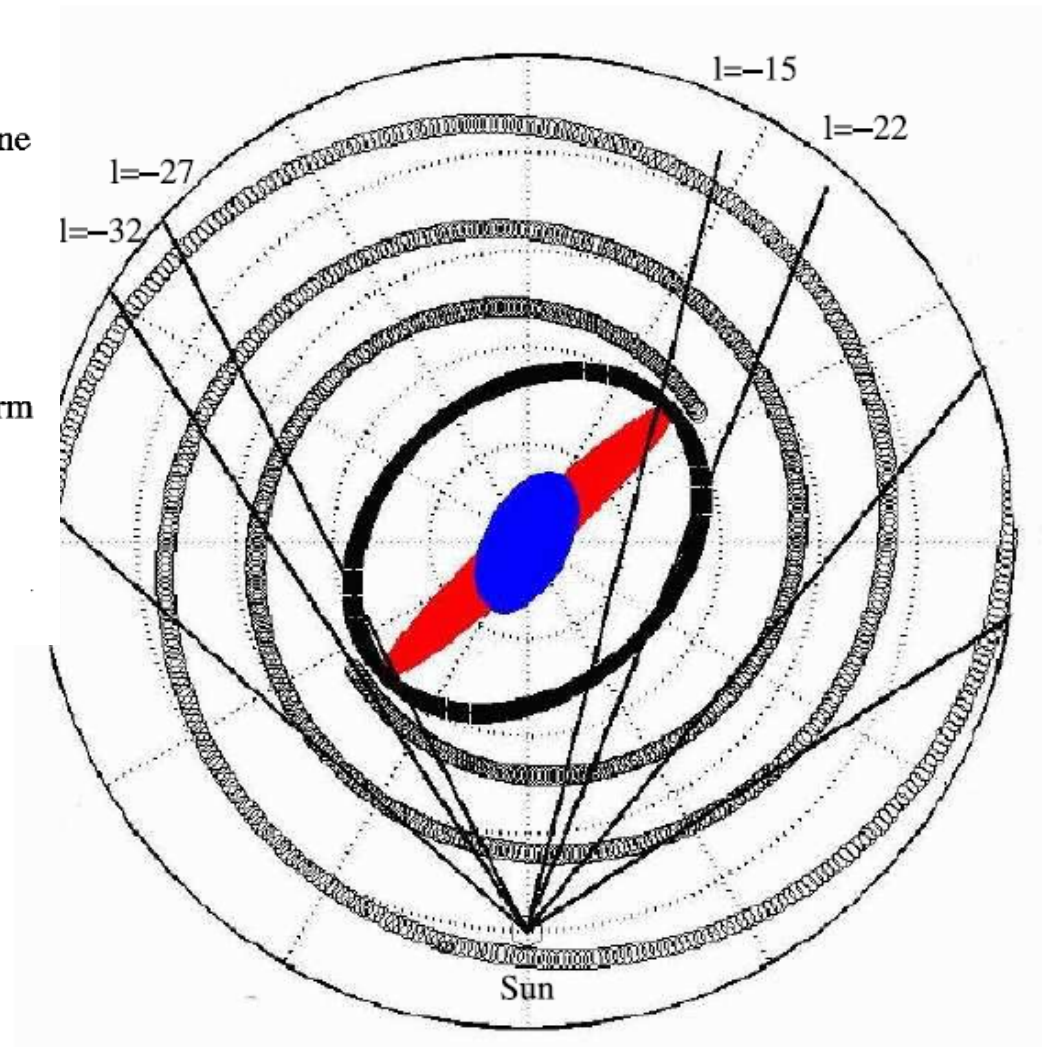
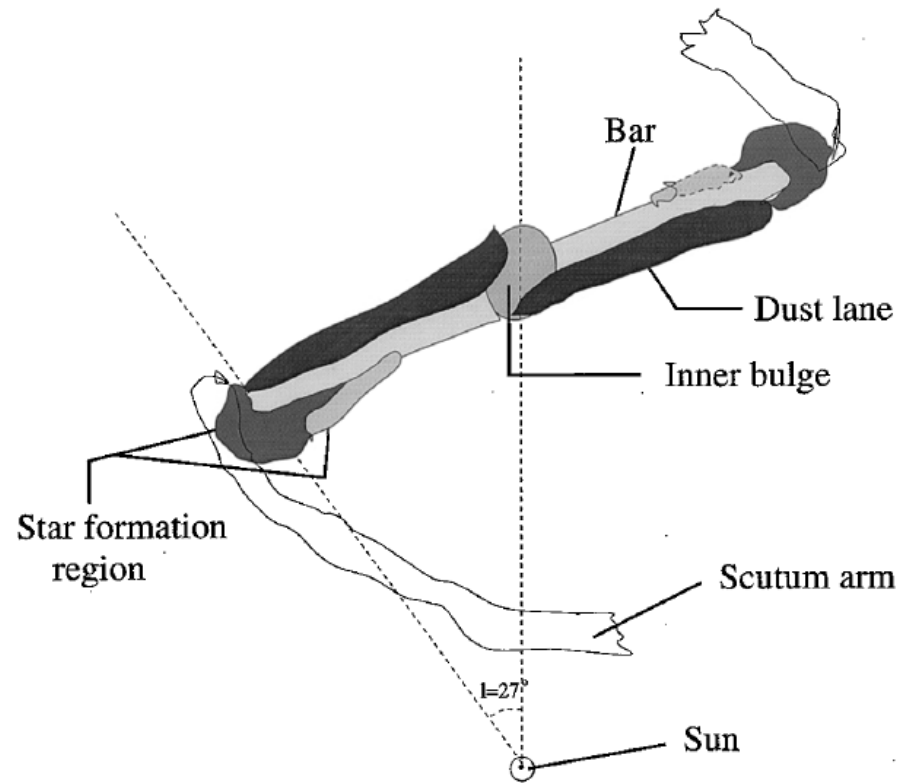


Fig. 5. The distribution of HII regions and GMCs ( $R_0 = 8.5$  kpc and  $\Theta_0 = 220$  km s<sup>-1</sup>) and the best-fitting two-arm model (top panel), three-arm model (middle panel) and four-arm model (bottom panel).

# The Inner Galaxy and the Bar

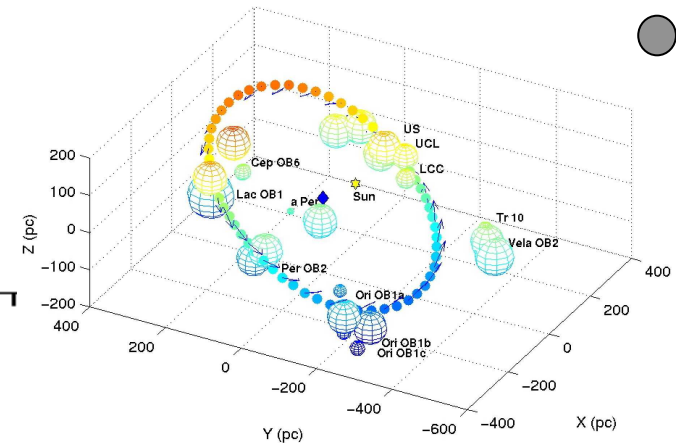
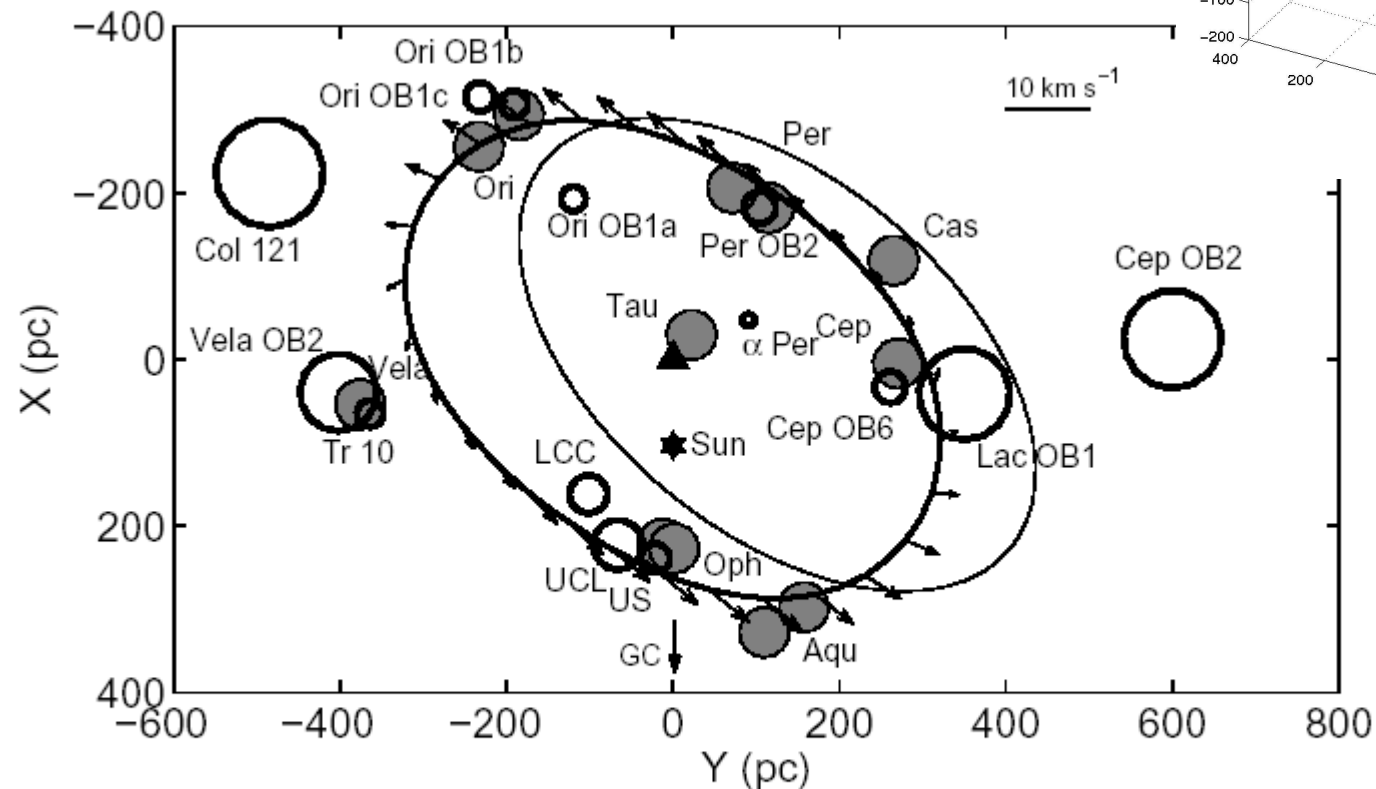


*Hammersley et al. 2007*



# The Gould Belt

C. A. Perrot and I. A. Grenier: 3D dynamical evolution of the Gould Belt



**Fig. 5.** Present position of the Gould Belt projected on the Galactic plane. The  $x$  and  $y$  axes point to the Galactic Centre and in the direction of the Galactic rotation, respectively. Both are centred on the Belt centre. The velocity field outlines the Belt expansion with respect to the Local Standard of Rest. Nearby OB associations are plotted as thick circles using *Hipparcos* estimates of their distance and dimensions from de Zeeuw et al. (1999). The shaded circles mark the location of the main nearby  $H_2$  cloud complexes. The thick and thin ellipses note the Belt rim as obtained in this work and earlier from the HI data by Olano (1982). The triangle and star note the Belt centre and the Sun, respectively.

# Galaxy Disk & Halo: High-Velocity Clouds

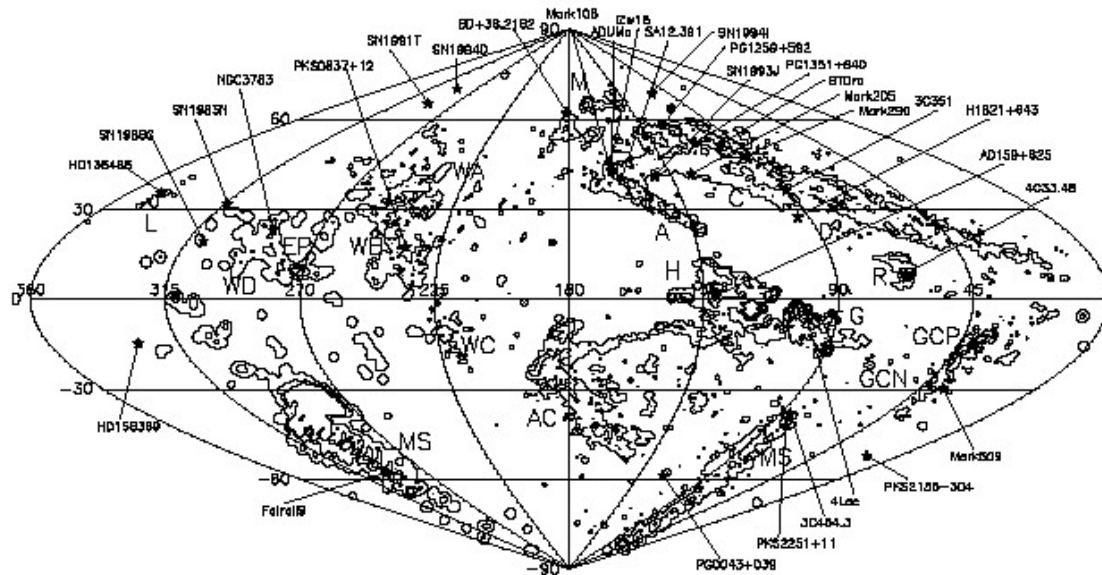


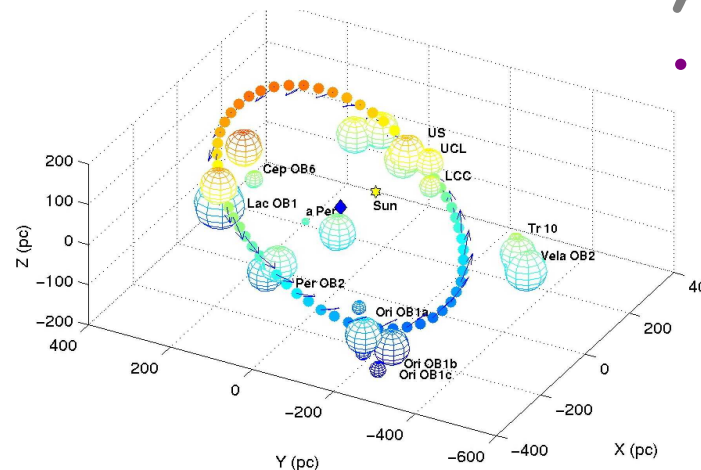
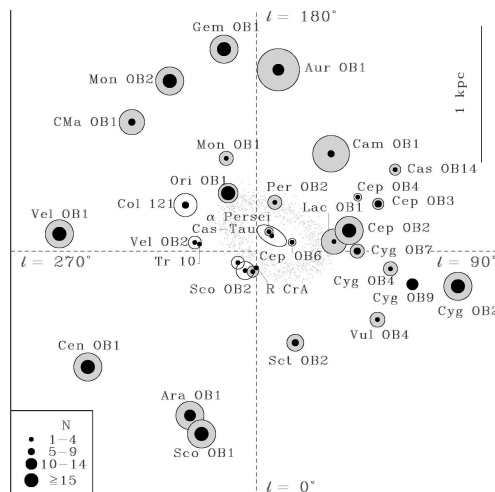
Figure 1 Brightness temperature map of HVCs (HI with  $|v_{\text{LSR}}| > 90 \text{ km/s}$ ). Contours at 0.04, 0.5, and 1.5K. Common names of some complexes are indicated. Background sources in which high-velocity absorption has been detected or claimed are indicated (see Table 3, Table 4, and Section 4).

- Neutral-Gas Clouds with Large Latitudinal Velocities

★ Define: HVC =  $> 90 \text{ km s}^{-1}$  (LSR)

★ Typical  $M \sim 10^5 M_{\odot}$ ,  
 $\rightarrow E_{\text{kin}} \sim 10^{52} \text{ erg}$

Wakker & vanWoerden, 1997



## Application:

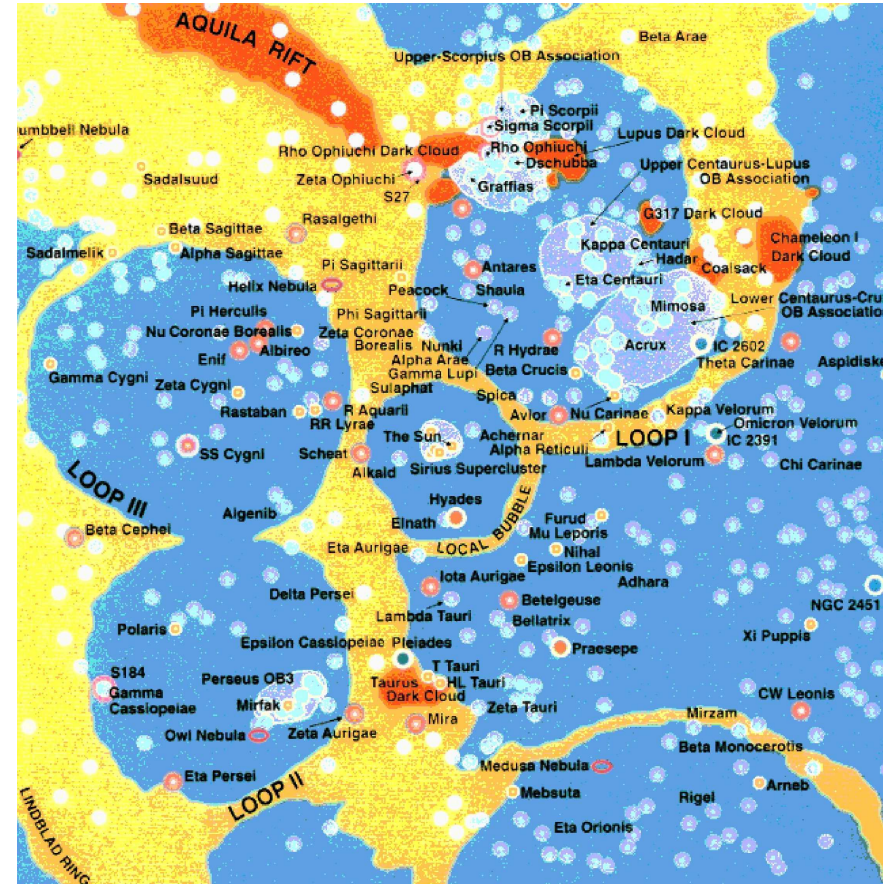
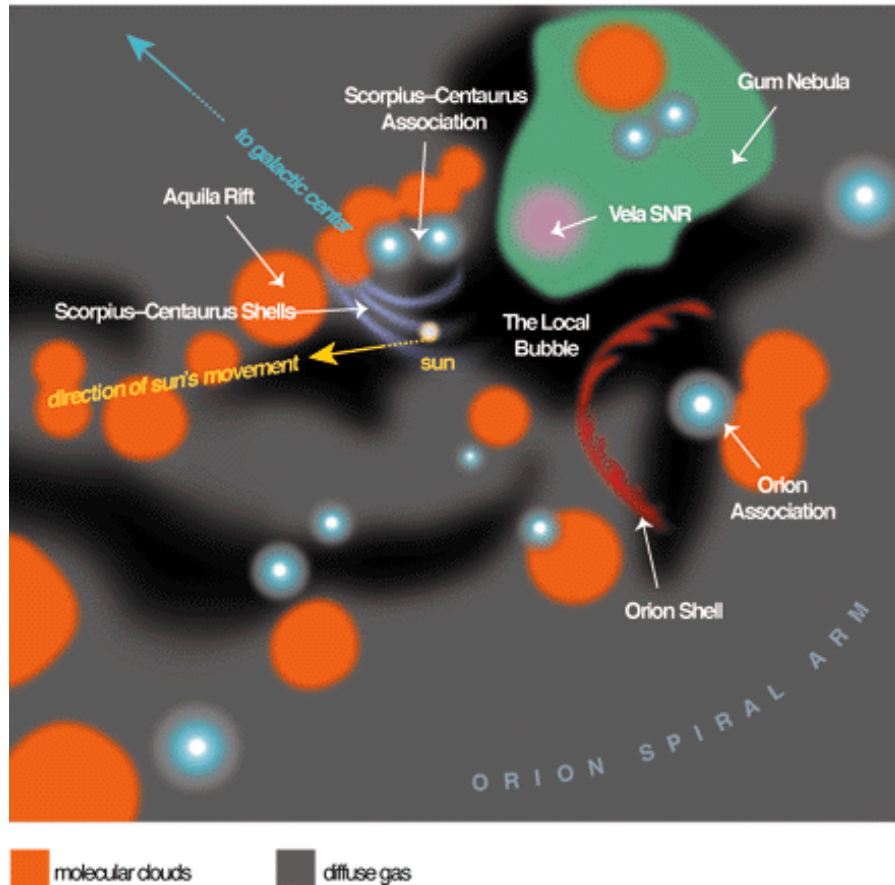
- Gould Belt System of OB Associations: From Impact of HVC?

➡ Oscillation around Disk Gravitational Well

➡ Triggered Star Formation



# Local ISM Morphology



- Massive Stars Shape ISM, Low-Mass Stars are Embedded
  - ➡ OB Associations
  - ➡ Swept-Up Shells, Cooling Cavities

# Star-Forming Complexes in the Galaxy

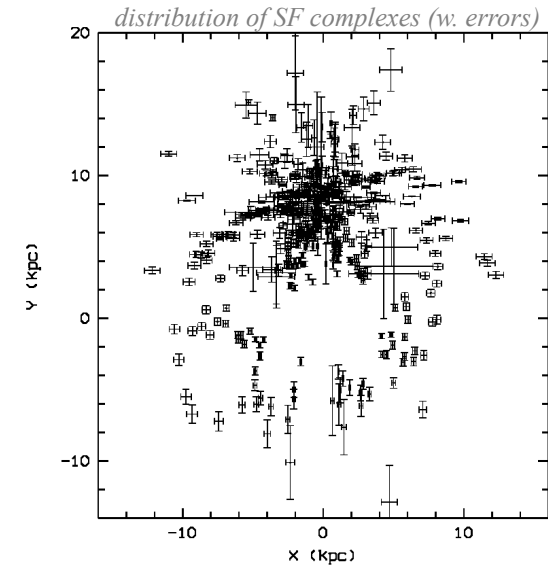
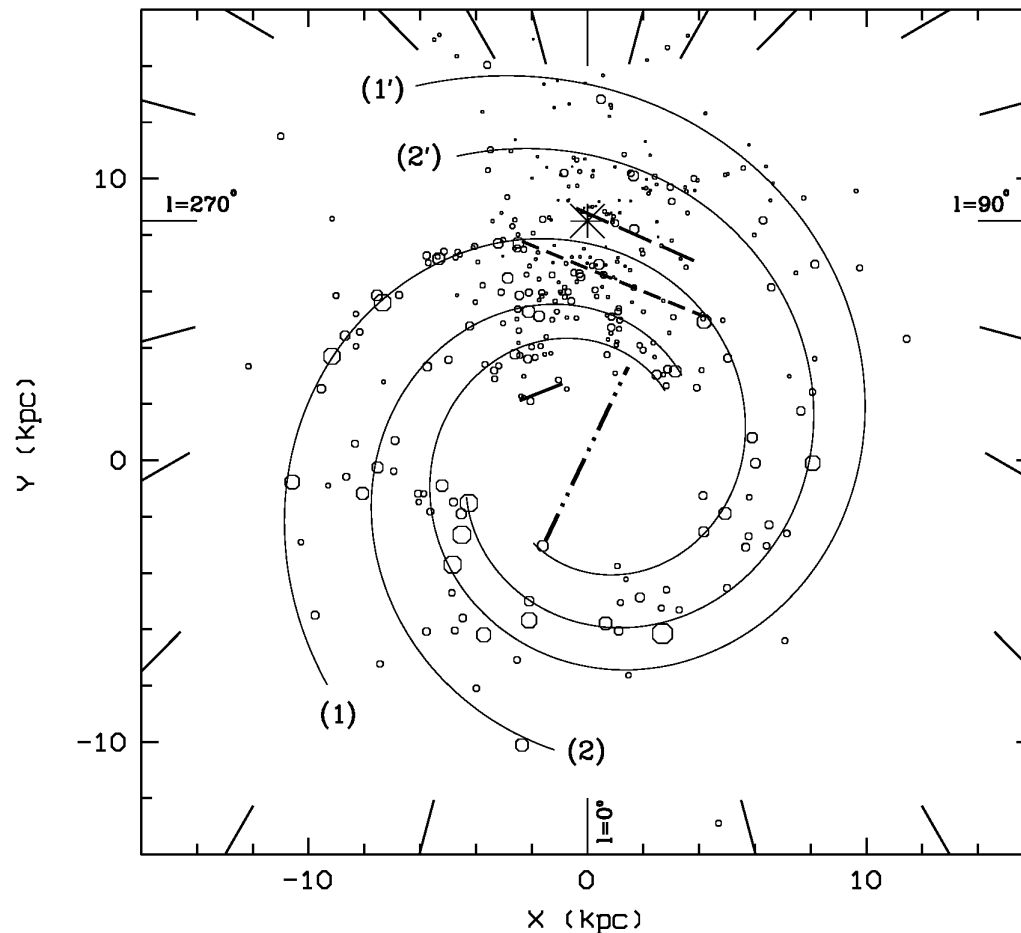


★ Group Star Clusters & HII Regions According to Kinematics and Spatial Associations

☞ Reduced Uncertainties in D

★ Compare to 4-Arm Spiral

☞ Gas may be 2-Arm Spiral; Stars best fit by 4 Arms



- ★ Sag-Car Arm (1)
- ★ Scu-Crx Arm (2)
- ★ Nor-Cyg Arm (1')
- ★ Per Arm (2')
- ★ Local Arm

☞ D. Russeil, A&A, 2003

# Constituents of the ISM

constituents of ISM in Milky Way	where	temperature density ...	how observed
atomic hydrogen HI	in disk, some in halo $\approx 90\%$ of mass, 50% of vol.	50...300K $1...100\text{cm}^{-3}$	21cm radio line UV absorption lines
molecular hydrogen H <sub>2</sub>	dark clouds in disk $\approx 10\%$ of mass, 1% of vol.	3...100K $10^2...10^6\text{cm}^{-3}$	UV absorption lines IR emission lines
other molecules CO, HCN, H <sub>2</sub> O ...	dark clouds in disk	3...100K $10^2...10^6\text{cm}^{-3}$	radio and IR emission
ionized hydrogen HII	near hot stars, emission nebulae	5000...10000K $10^2...10^4\text{cm}^{-3}$	optical and IR emission lines, radio continuum
hot gas	everywhere	$10^6...10^7\text{K}$ $0.01\text{cm}^{-3}$	X-ray emission
dust grains	mostly in disk $\approx 1\%$ of mass	20...100K size $\approx 2000\text{\AA}$	reddening/absorption of starlight, IR emission
magnetic fields	everywhere	$\mu\text{Gauss}$	polarization of stars, Zeeman effect, synchrotron radiation
cosmic rays	everywhere	energies up to $10^{20}\text{eV}$	air showers

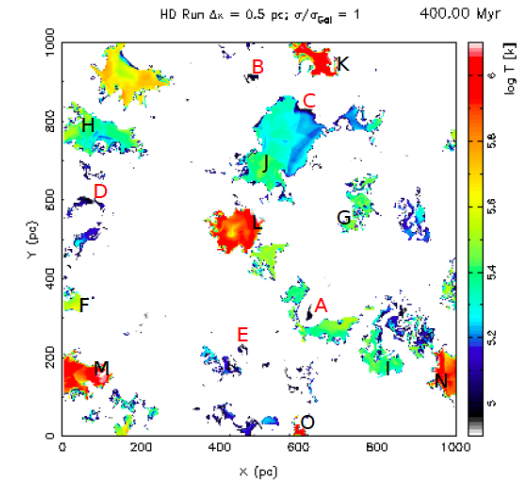
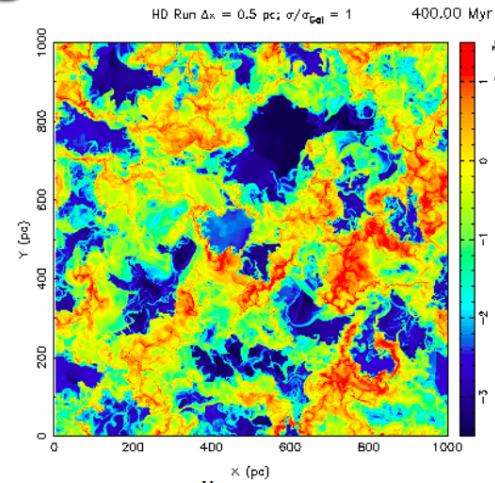
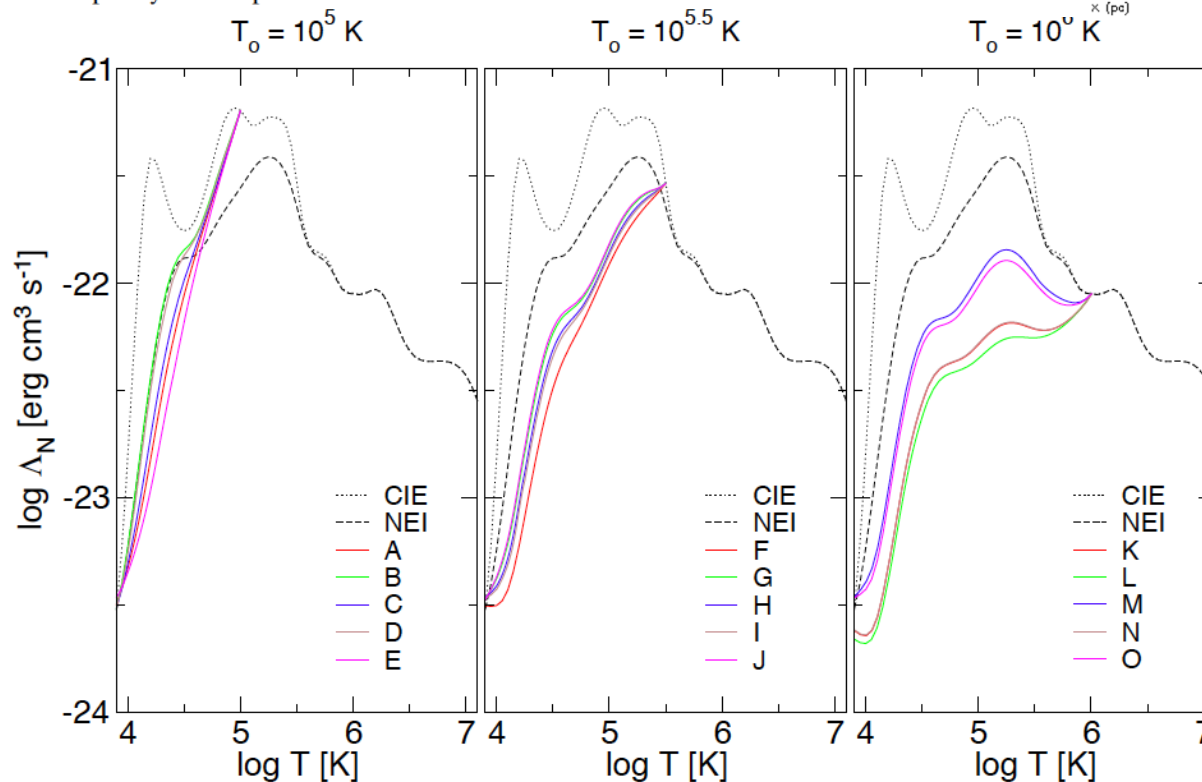
- **ISM Fraction of Total Galactic Mass: ~15%**  
(typical for spiral galaxies)
- **Cloud Fraction ~50% (1-2% by Volume)**

# Cooling of Hot ISM

- Non-equilibrium gas
- ★ Cooling rate variety (r,T)

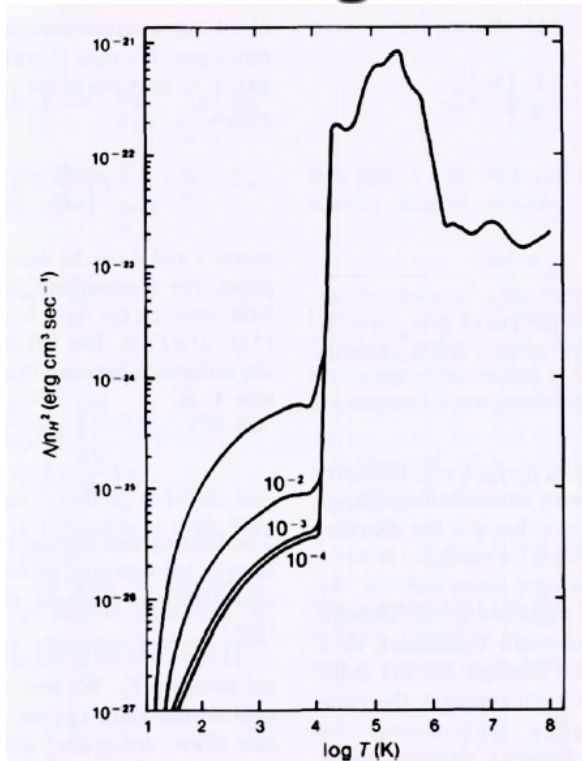
👉 Breitschwerdt+ 2012

**Fig. 4** Normalized NEI cooling functions at different locations in the Galactic midplane, corresponding to the labels in Fig. 3 (right panel) with initial temperatures of  $10^5$  K (labels A–E),  $10^{5.5}$  K (labels F–J), and  $10^6$  K (labels K–O), respectively. The black dotted and dashed lines represent the CIE and NEI cooling, respectively. The latter was calculated for isochoric cooling of a completely ionized plasma at  $10^9$  K.





# Cooling of Interstellar Gas

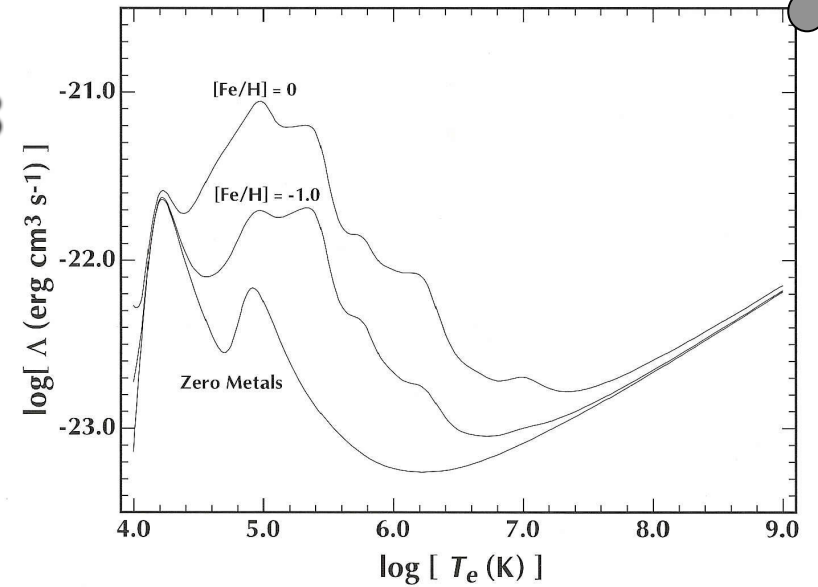


**Figure 18.4.** Cooling function for interstellar gas. For  $T < 10^4$  K, different curves correspond to different values of  $n_e/n_H$ . For  $T > 10^4$ ,

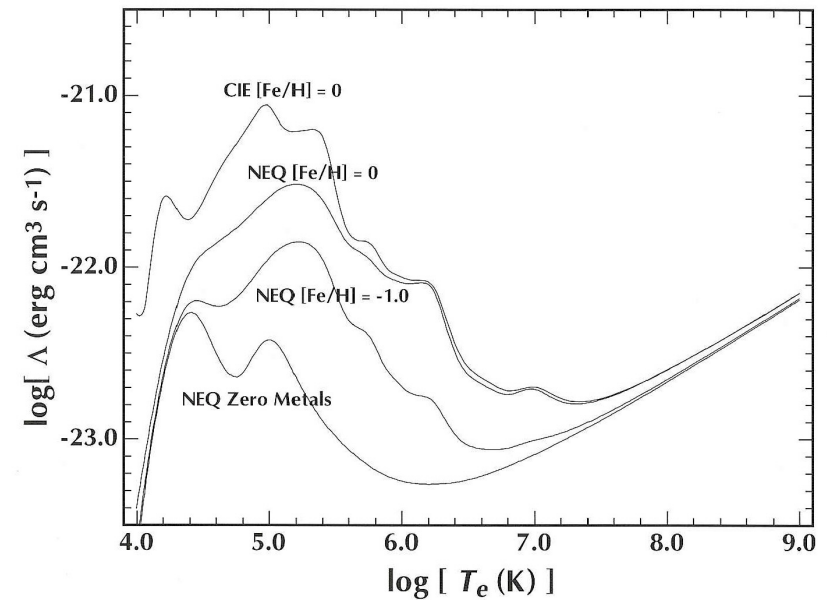
$$\tau_{\text{cool}} = \frac{3/2 N k_B T}{\Gamma - \Lambda}$$

• Cooling Function:

★ Importance of Equilibrization



**Fig. 7.1.** The collisional-ionization cooling function as a function of metallicity. At zero “metals” (elements heavier than helium), the peaks due to hydrogen and helium are apparent, while those of carbon, oxygen, neon, silicon, and iron become apparent in the other curves (after Sutherland & Dopita, 1993).



**Fig. 7.4.** The cooling function under conditions of nonequilibrium cooling as a function of metallicity. Note how the peaks of Fig. 7.1 are smeared out (after Sutherland & Dopita, 1993).

# ISM as a Pressure-Balanced Equilibrium

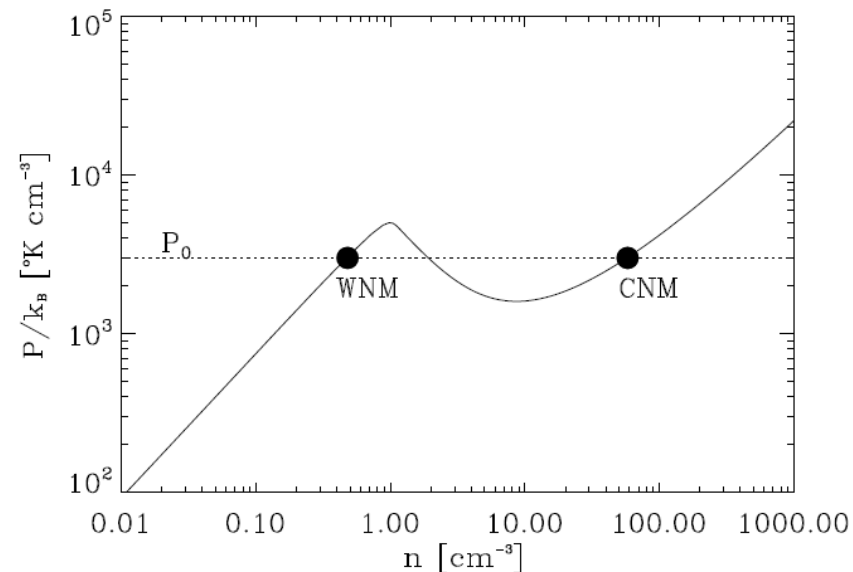
## ★ Assume Heating and Cooling Rates in Equilibrium

☞ Radiative Cooling and Shock Heating

## ★ Assume Pressure Balance

- Need a Positive (stabilizing) Gradient in pressure-density Relation
- Phase Diagram Produces Two Intersections for a Given Pressure

☞ Two Phases: Cold and Warm Neutral Medium

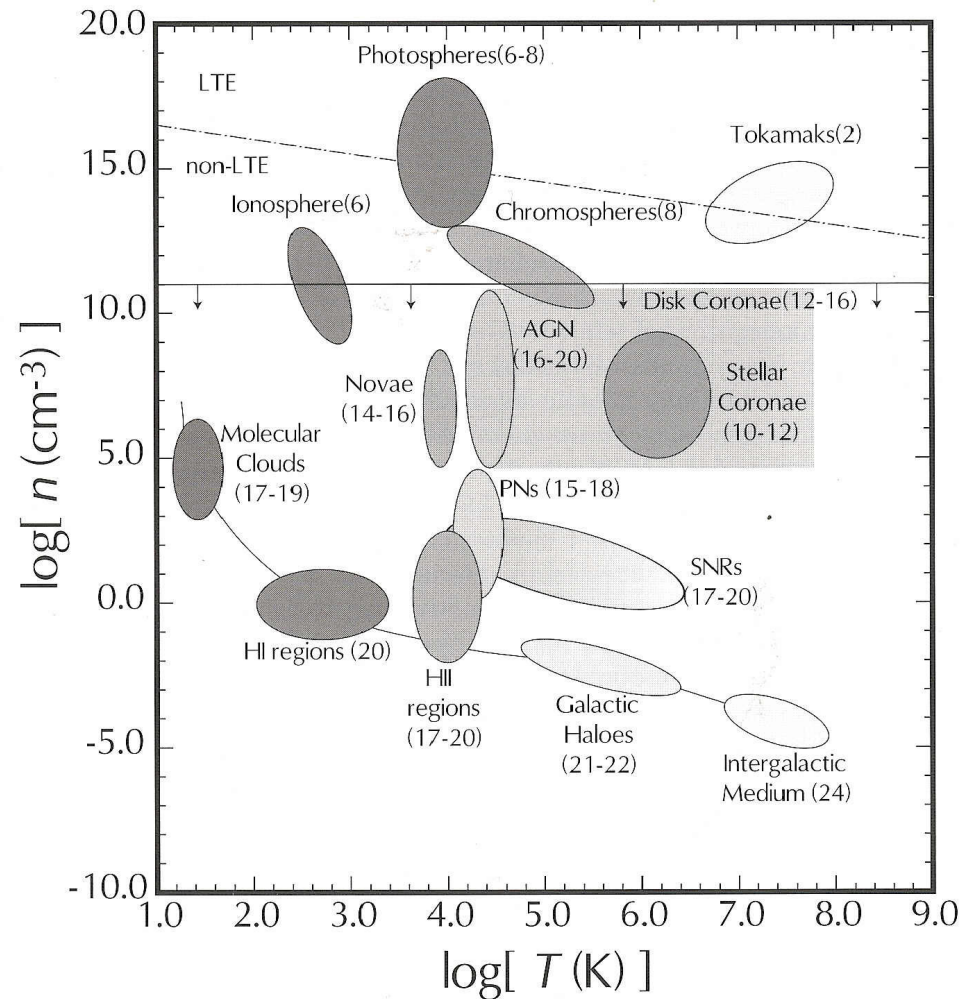


☞ Pikel'ner (1968), Field (1969), Goldsmith, Habing (1969)

# Diffuse Cosmic Plasmas



- **Interstellar Medium**
  - ★ **Cold Clouds**
  - ★ **Diffuse Clouds**
  - ★ **Hot Cavities**
  
- **Sources of Turbulent Energy**
  - ★ **SNe**
  - ★ **Winds**



**Fig. 1.2.** Densities and characteristic sizes of diffuse astrophysical plasmas in the universe. For each class of objects, the characteristic size in  $\log(\text{cm})$  is given. The approximate boundary between plasmas in LTE and non-LTE plasmas is marked as a dash-dot line. The diffuse universe lies approximately below the horizontal line marked with arrows. The thin solid curve connects the dominant phases of galactic and intergalactic diffuse media.

# What Shapes the ISM?



- Classical View

- ★ Observations of Smooth Line Profiles

- => ISM is Composed of "Phases" with Typical Characteristics

- ☞ Scales, Temperatures, Pressures: Pressure Equilibrium @  $P/k \sim 10^4 \text{ K cm}^{-3}$

- ★ Models:

- ☞ Self-Gravity is Responsible for Clumping & Star Formation

- ☞ Magnetic Fields Modify Fluid Characteristics

- ☞ Supernovae and Density Waves Provide the Energy

- ☞ *e.g. McKee & Ostriker 1977*

- Revised Current View

- ★ Observations of Power Laws in Scales, Energy, ...

- ★ Turbulence on all Scales

- ★ Models:

- ☞ Supernovae Provide the Turbulent-Energy Input  
(+ many other secondary sources)

- ☞ ISM is Constantly Evolving, No Equilibrium, all Structures are Transient

- ☞ *e.g. MacLow & Klessen (2004), Elmegreen & Scalo (2004)*

# Turbulent Energy in the ISM

☆ Processes of  $E_{kin} \rightarrow$  Turbulence not understood

- Energy Sources:

☆ Stars  $E_{kin} \approx 1...2 \times 10^{-25} \text{ erg} \cdot \text{cm}^{-3} \text{ s}^{-1} \rightarrow E_{turb} \approx 3 \times 10^{-26} \text{ erg} \cdot \text{cm}^{-3} \text{ s}^{-1}$

☞ WR Winds

☞ Supernovae

☞ Injection Scale 50...500 pc

☆ Galactic Rotation

☞ Spiral-Arm Shocks

☞ Instabilities (Balbus-Hawley)

☞ Scattering of Cloud Complexes

$$E_{turb} \approx 3 \times 10^{-29} \text{ erg} \cdot \text{cm}^{-3} \text{ s}^{-1} \big| B = 3 \mu\text{G}$$

☆ Self Gravity

☞ Cloud Collapses

☞ Swing-Amplified Instabilities

☆ Fluid Instabilities

☞ Kelvin-Helmholtz Instability

☆ Galactic Gravity

☞ Disk-Halo Circulation

☞ Parker Instability

☞ Galaxy-Galaxy Interactions

# ISM Phases (??... current consensus...)

## ★ Hot Ionized Medium

☞ Observed as SNR / hot gas (X-rays)

## ★ Warm Ionized Medium

☞ Observed as free  $e^-$  ("Reynolds Layer")

## ★ Partially-Ionized Medium

☞ Observed indirectly (eg pulsar dispersion measure & WIM)

## ★ Cold Neutral Medium

☞ Observed as HI Gas, Molecular Gas, Dust

Quantity	HIM	RWIM	WNM/MOWIM	CNM
$h T, K$	$? \rightarrow 10^7$	$\sim 8000$	$500 \rightarrow 8000^A$	$10 \rightarrow 75^A$
$\frac{P}{k}, \text{cm}^{-3} K$	$\gtrsim 20000^B$	$\gtrsim 3400^B$	$200? \rightarrow 4000^A$	$1500 \rightarrow 10000$
$n, \text{cm}^{-3}$	0.003	$\sim 0.08$	$0.1 \rightarrow 0.4^A$	$20 \rightarrow 250$
$X_e$	1	1	$\sim 10^{-2} \rightarrow 0.5^A$	$\sim 2 \times 10^{-4} (= \frac{C}{H})$
$f$	$0.5^C$	$0.1^C$	$0.5^C$	$0.01^C$
$N_{20\perp}$	$\sim 0.3?^E$	$0.1?^E$	H, 1.9; e, $0.3?^E$	1.8
Heating	shocks	H photoion + ?	grains, etc <sup>D</sup>	C ionization, etc <sup>D</sup>
Ionization	el coll	H photoion	H XR, some CR	C photoion, some CR
Observing	XR, UVA, UVE	DM, EM, SM, UVA, FS	HIem, UVA, IRe, FS	HIe, HIIa, UVA, IRe, FS

In column 1,  $X_e$  is the ionization fraction  $\frac{n_e}{n_e + n_{HI}}$ ;  $f$  is volume filling fraction;  $N_{20\perp}$  is the H or electron column density projected towards the Galactic pole in units of  $10^{20} \text{ cm}^{-2}$ . In other columns, XR is X-Ray emission; DM pulsar dispersion; EM H $\alpha$  emission; SM pulsar scattering; FS fine structure lines in emission; IRe continuum IR emission from grains; UVA optical/UV absorption lines against stars; UVE UV emission lines; HIe and HIIa 21-cm line emission and absorption.

<sup>A</sup> This quantity is critically discussed herein and these values may be either not correct or not generally accepted.

<sup>B</sup> These are typical pressures; wide fluctuations exist.

<sup>C</sup> Volume filling factors depend on  $z$  and are highly uncertain; these values are for  $z = 0$ .

<sup>D</sup> In contrast to the other phases, multiple heating mechanisms are important for the WNM and CNM; see Figure 3 of Wolfire et al (1995a).

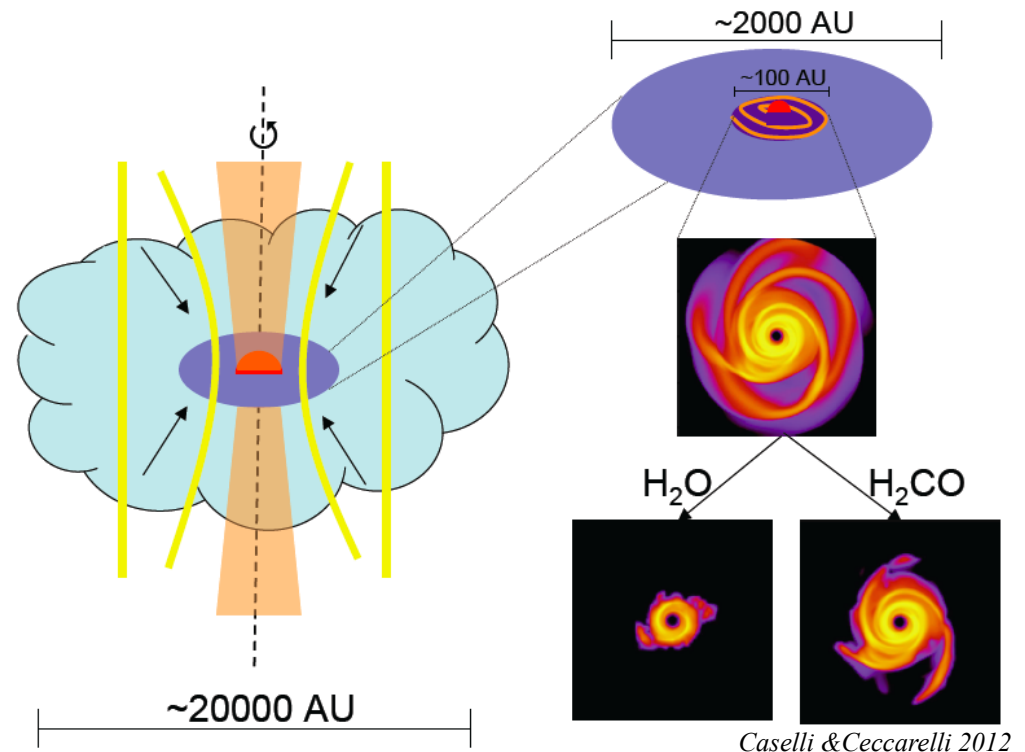
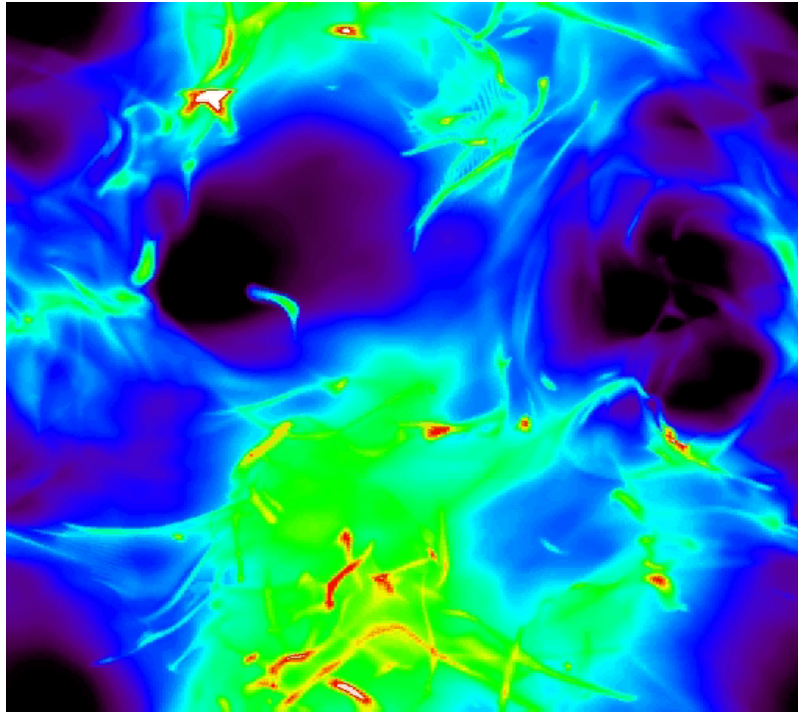
<sup>E</sup> The  $N_{e\perp}$  for the HIM is a theoretical value (Wolfire et al 1995b). The relative contributions of the RWIM and the MOWIM to  $N_{e\perp}$  are arbitrarily chosen and are highly uncertain (§§).



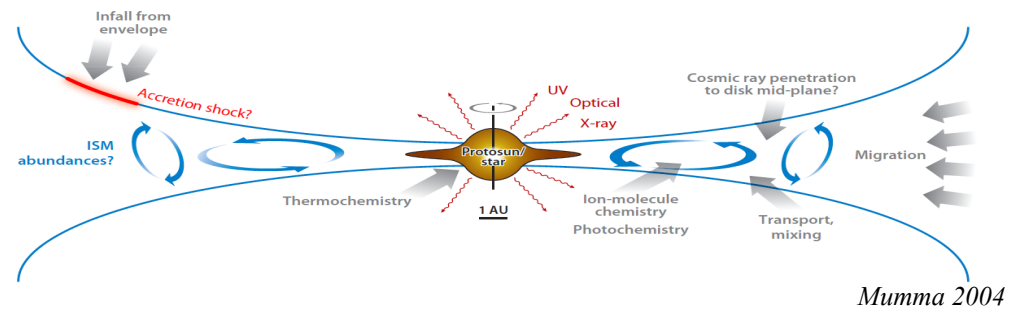
# How molecular gas ends up in a new star



Vasileiadisi 2013



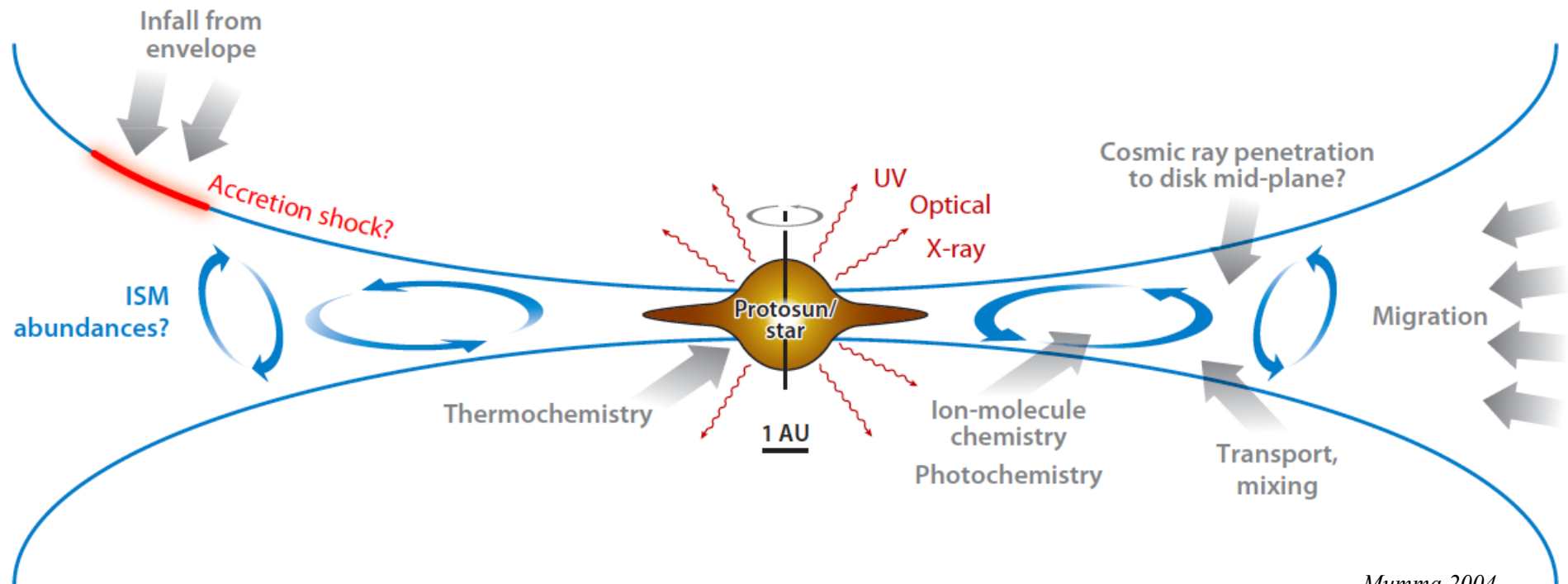
- Out of a dynamic ISM a concentration of gas cools, contracts, forms a protostar, which slowly grows until becoming a young star



# Early Solar System Processes

- ★ Around the protostar, material accretes through a disk
- ★ Disk is fed from outside, and includes a variety of
  - ☞ Chemistry: cold in outer disk, hot near protostar, surface
  - ☞ Solidification of bodies in disk centroid, transported inwards
  - ☞ Jet with CAI formation and partial ejection at inner disk rim

- Planetesimal formation in disk





## Issues

- ☞ **Chemical reaction rates are very sensitive to ionization ( $H^+$  abundance)**
  - Cosmic ray penetration into clouds and protostellar disks?
  - Radioactive ionization in dense disks?
  
- ☞ **Reaction rates for cold chemistry, spin equilibrations?**
  
- ☞ **Grain morphology, ice layers?**
  - Ices sublimated near protostar, waterless chemistry?
  
- ☞ **Protostellar disk complexities**
  - Rapid inward flows
  - Vertical gradients of temperature and composition
  - Disk (molecular) wind

# Stability of Cosmic Gas Clouds

- gravitational instability (Jeans)

Criterion:  $M > M_J$

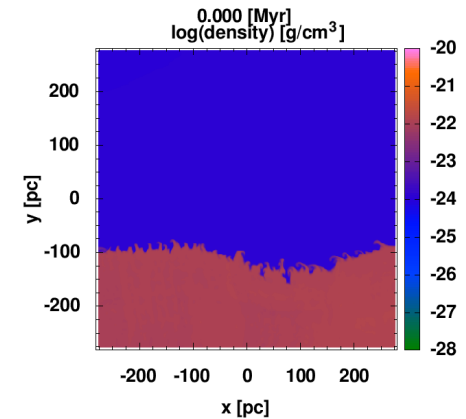
With Jeans mass

$$M_J = \frac{\pi^{5/2}}{6} \left( \frac{\mathcal{R}}{G} \right)^{3/2} \cdot \rho^{-1/2} T^{3/2} = \frac{\pi^{5/2}}{6} G^{-3/2} \cdot \rho^{-1/2} c_s^3$$

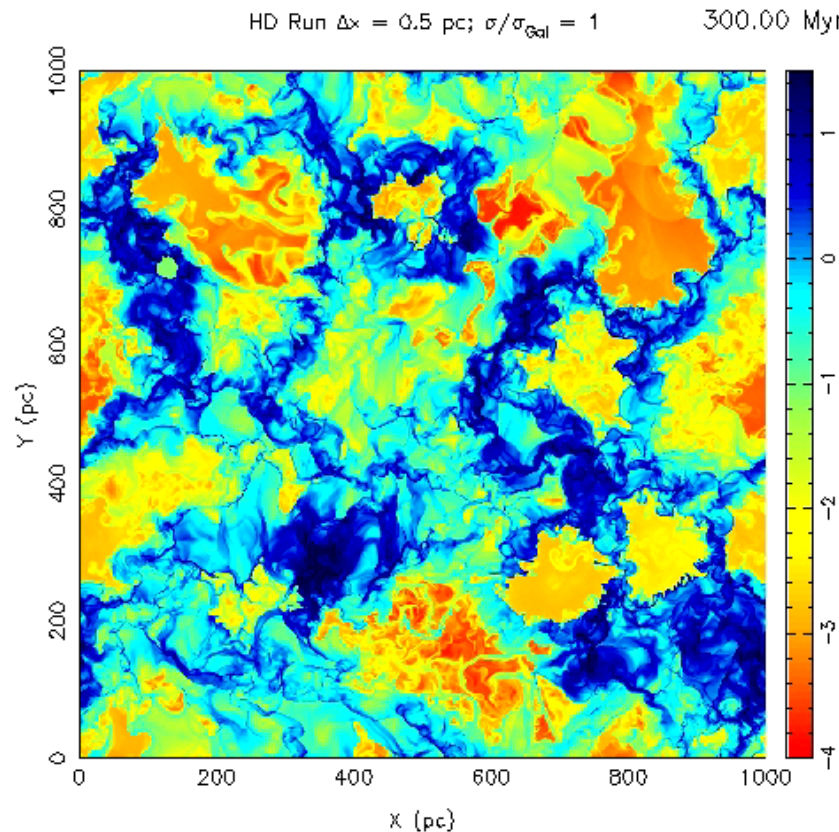
# The ISM: Learning from Models

- Numerical Simulations of ISM (MHD 3D)

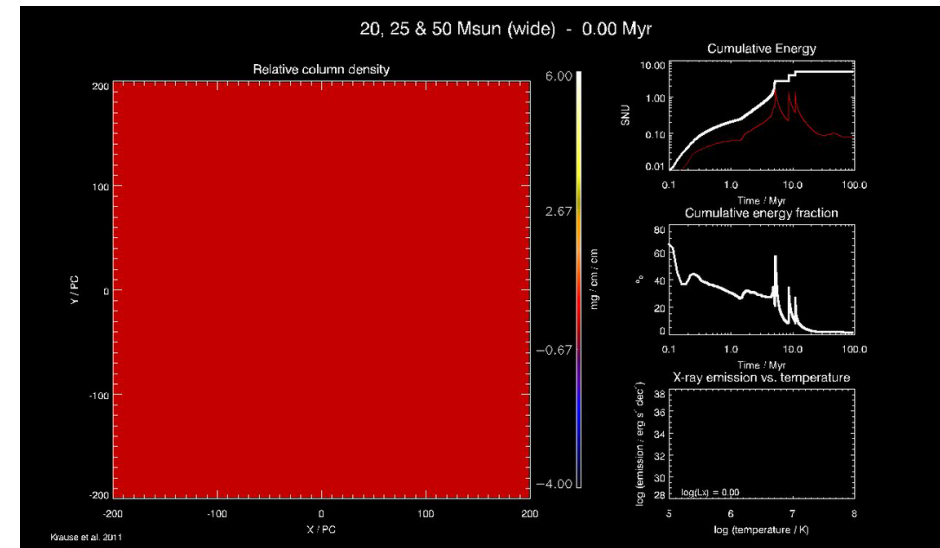
- ★ Multi-Scale Dynamics and Evolution
- ★ MC Outflows, Destruction, Chimneys
- ★ Energy Feedback into ISM



*Fierlinger+ 2012; Krause+ 2012, 2013*

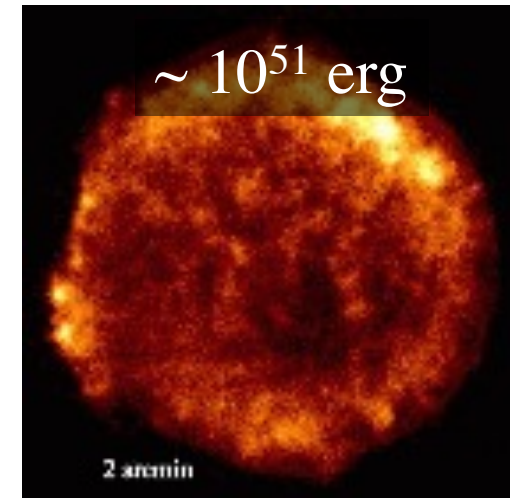
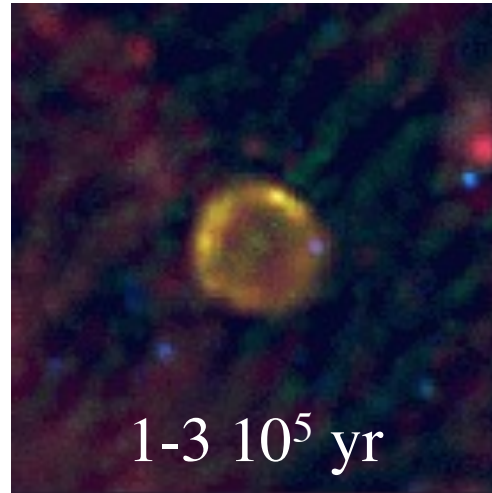
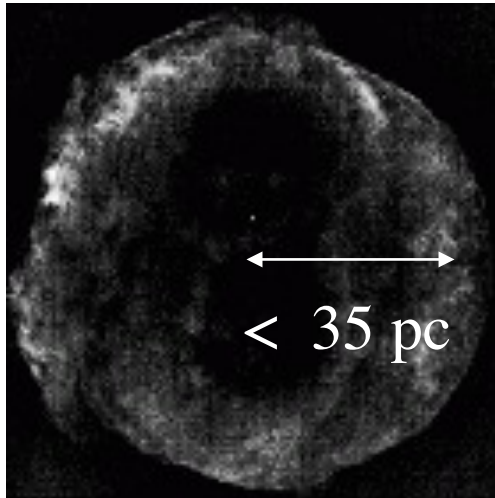


*DeAvillez&Breitschwerdt 2012*

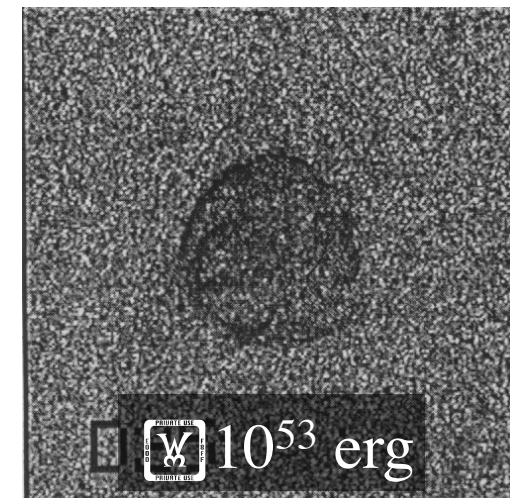
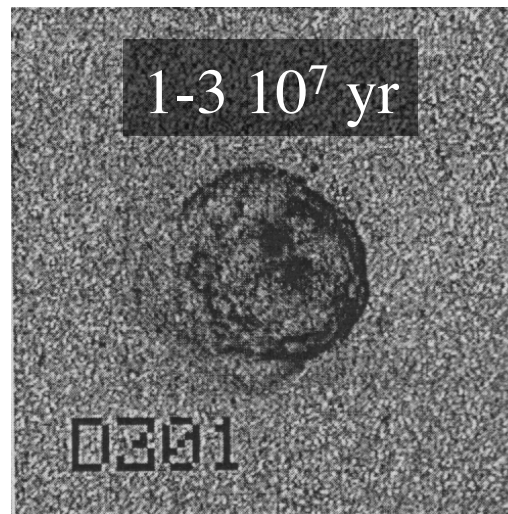
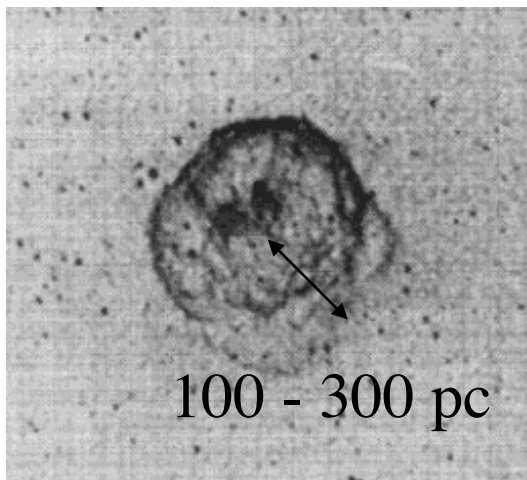


# Bubbles and superbubbles

S  
N  
R

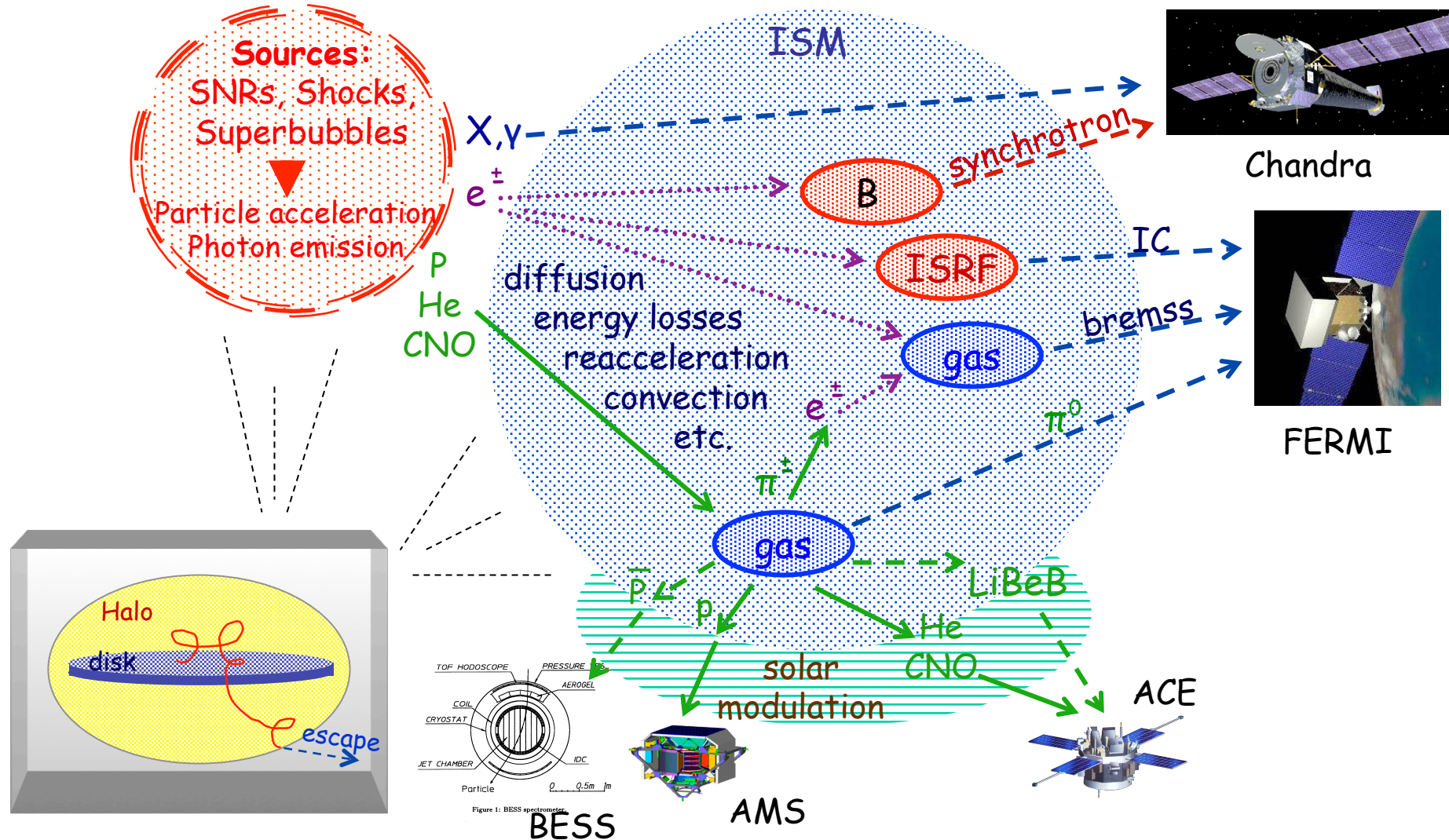


S  
B





# Cosmic Rays: From Sources to Observation



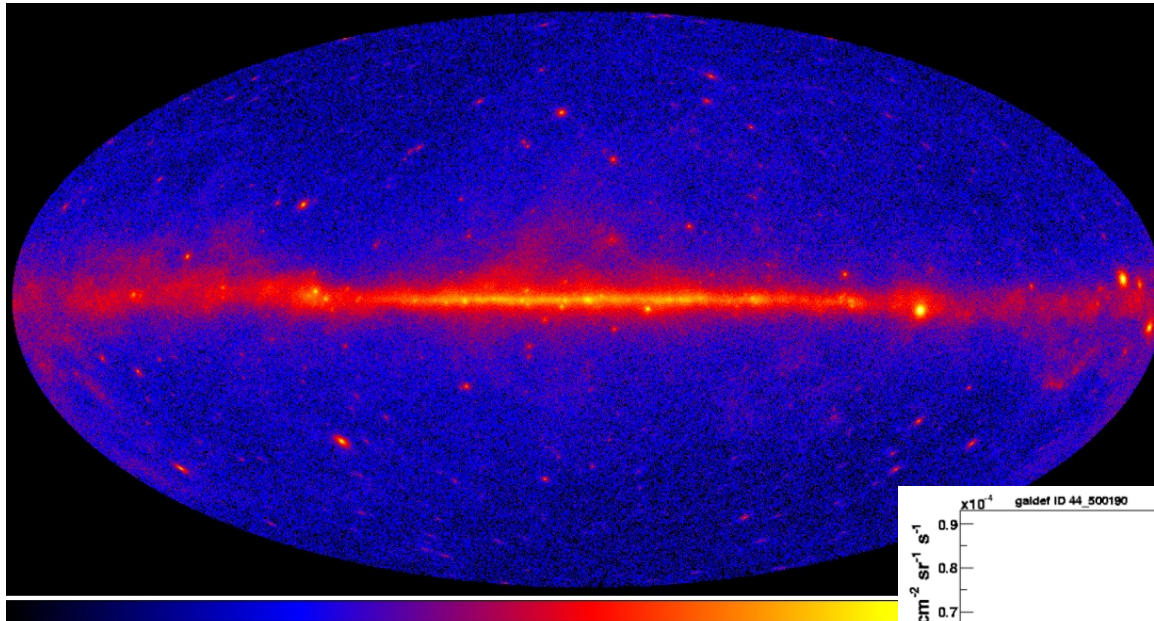
courtesy I. Moskalenko

# Illuminating Interstellar Gas with Cosmic Rays

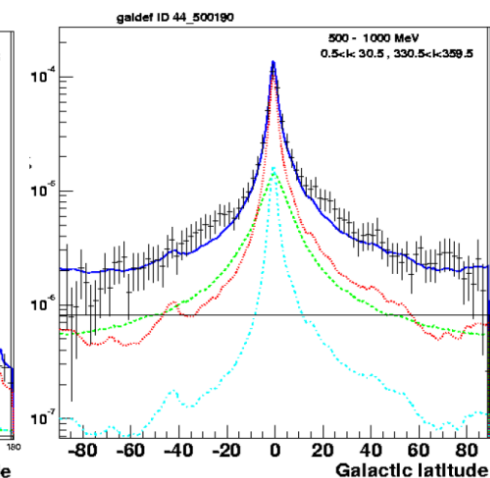
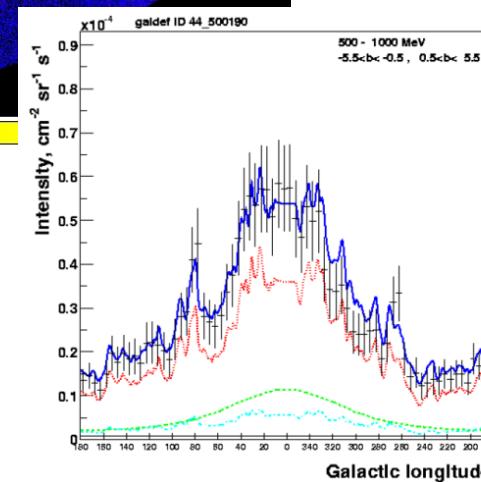
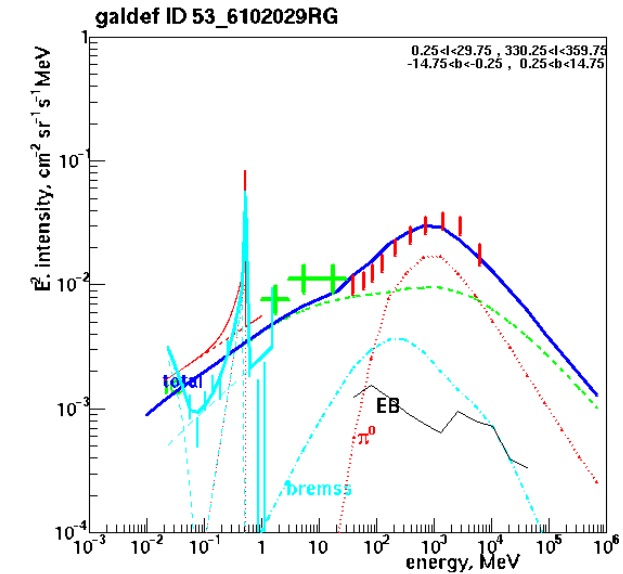


## ★ Gamma-Ray Emission from Cosmic-Ray / Gas Interactions

☞ Bremsstrahlung, Pion Production and Decay,  
Inverse-Compton Emission



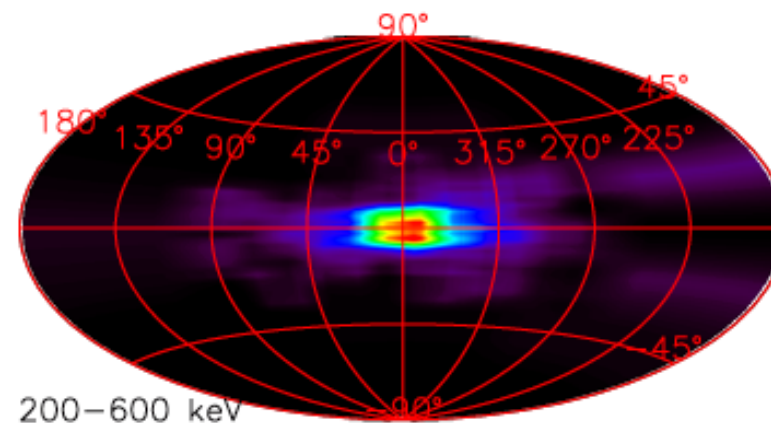
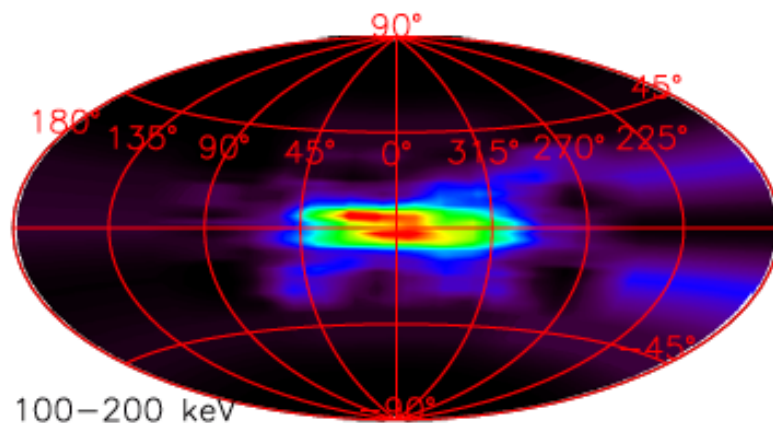
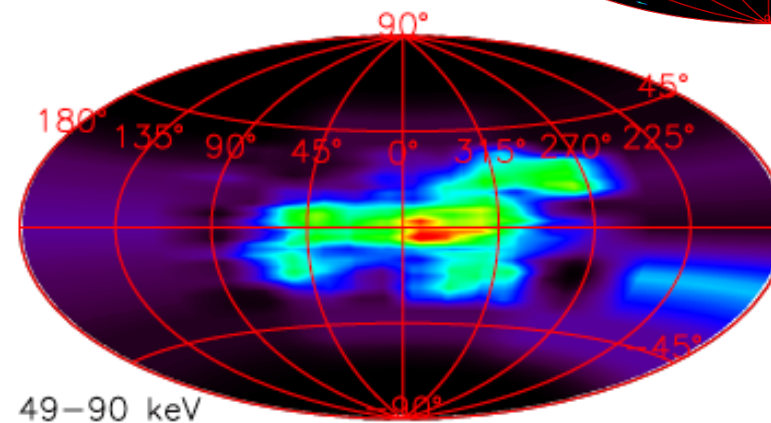
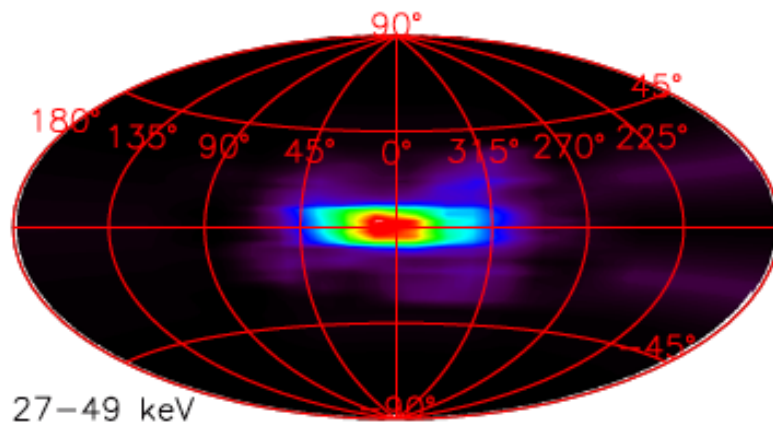
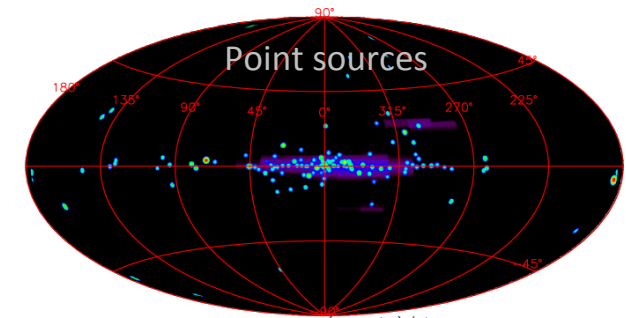
☞ Total-Gas Maps are a  
Good Model for  
Large-Scale  
Diffuse Gamma-Ray Emission



# Diffuse Emission: hard X-rays

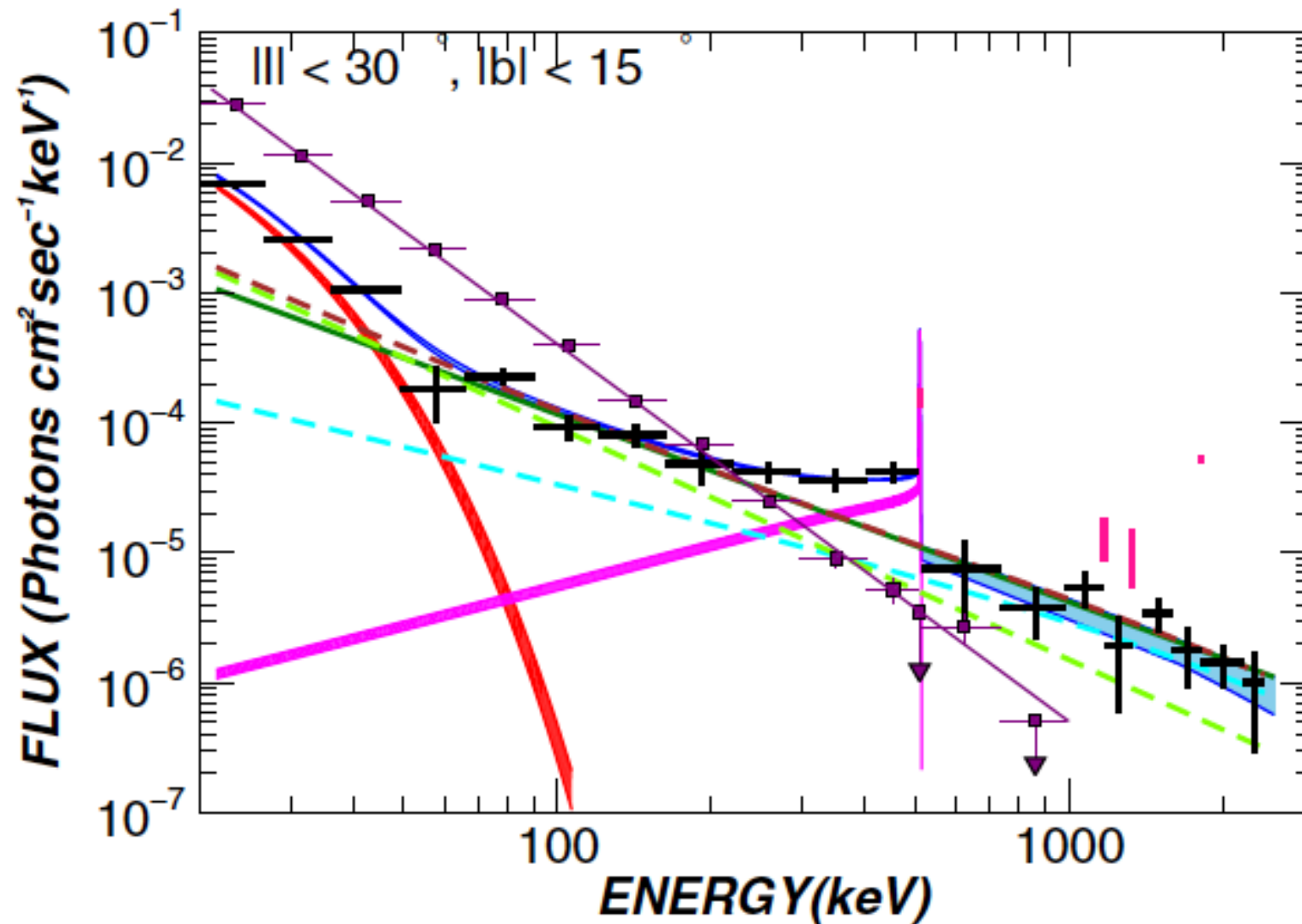
- Diffuse galactic emission detected above  $\sim 100$  keV

👉 SPI/INTEGRAL, Bouchet et al. 2011



# Understanding Diffuse Galactic Emission

- Interactions of Cosmic Rays with ISM Gas and ISRF

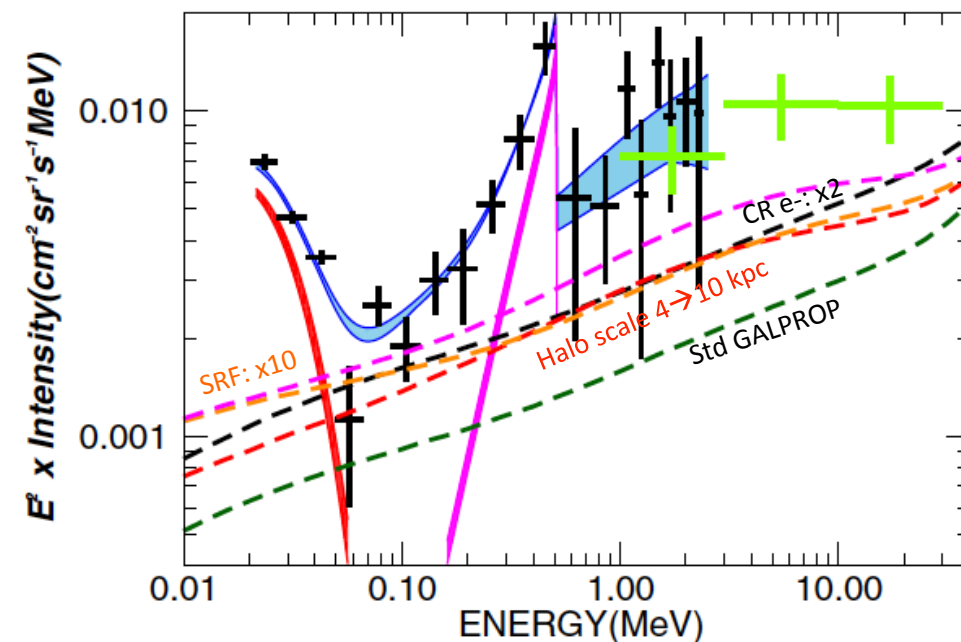
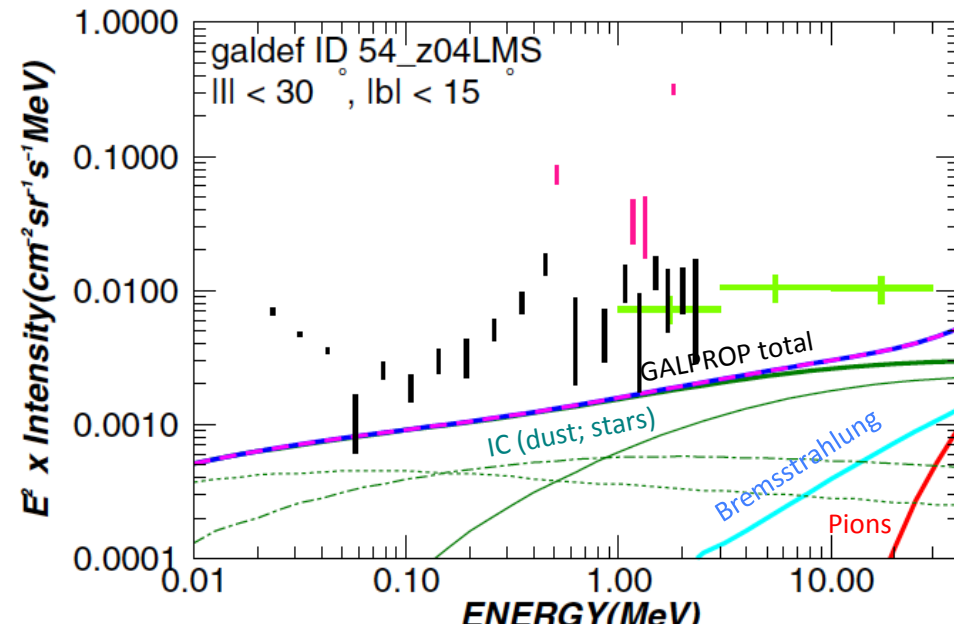




# Understanding Diffuse Galactic Emission

- In Detail:
  - ★ Interactions of Cosmic Rays with ISM Gas and ISRF
  - ★ Positron Annihilation
  - ★ Radioactivity Lines  $^{26}\text{Al}$ ,  $^{60}\text{Fe}$
  - ★ ( $\sim\text{MeV-}$ ) Sources (PL) (pulsars?)
- Observed Flux Exceeds CR-Model Predictions
  - ★ Enhancement in CR electron intensity?
  - ★ Enhancement in ISRF?

👉 Bouchet et al. 2011



# Evolution of Gas Composition

- “Chemical Evolution”

- ★ **Interstellar Gas**

- **Formation of Stars**

- ★ **Stellar Evolution**

- **Nuclear Fusion  
of Heavier Nuclides**

- **Dispersion of Ejecta**

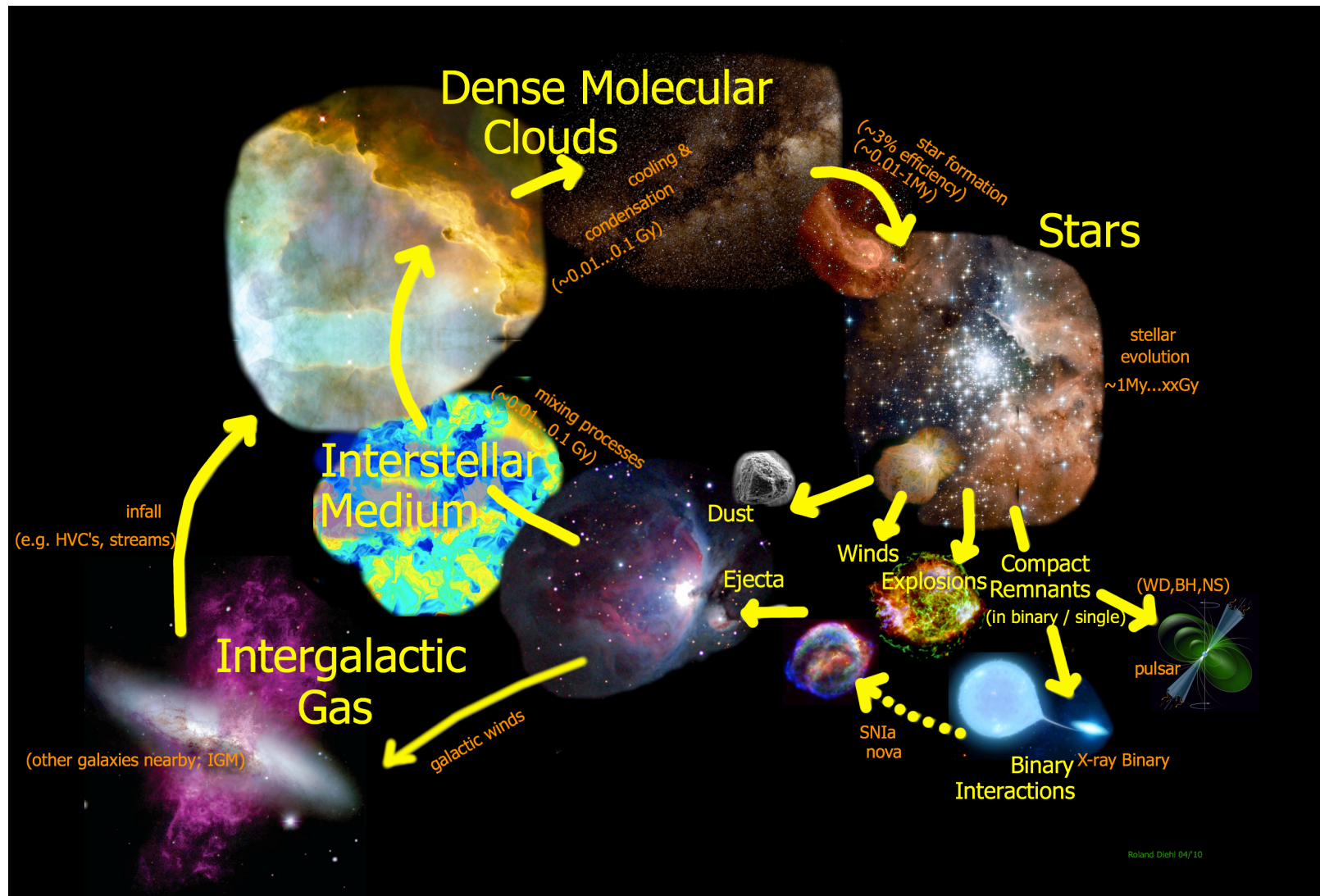
- **Conditioning of ISM**

- ★ **Galactic Evolution**

- **Gas Flows → Adding & Ejecting**

- **Conditioning of ISM**

# Describing Compositional Evolution



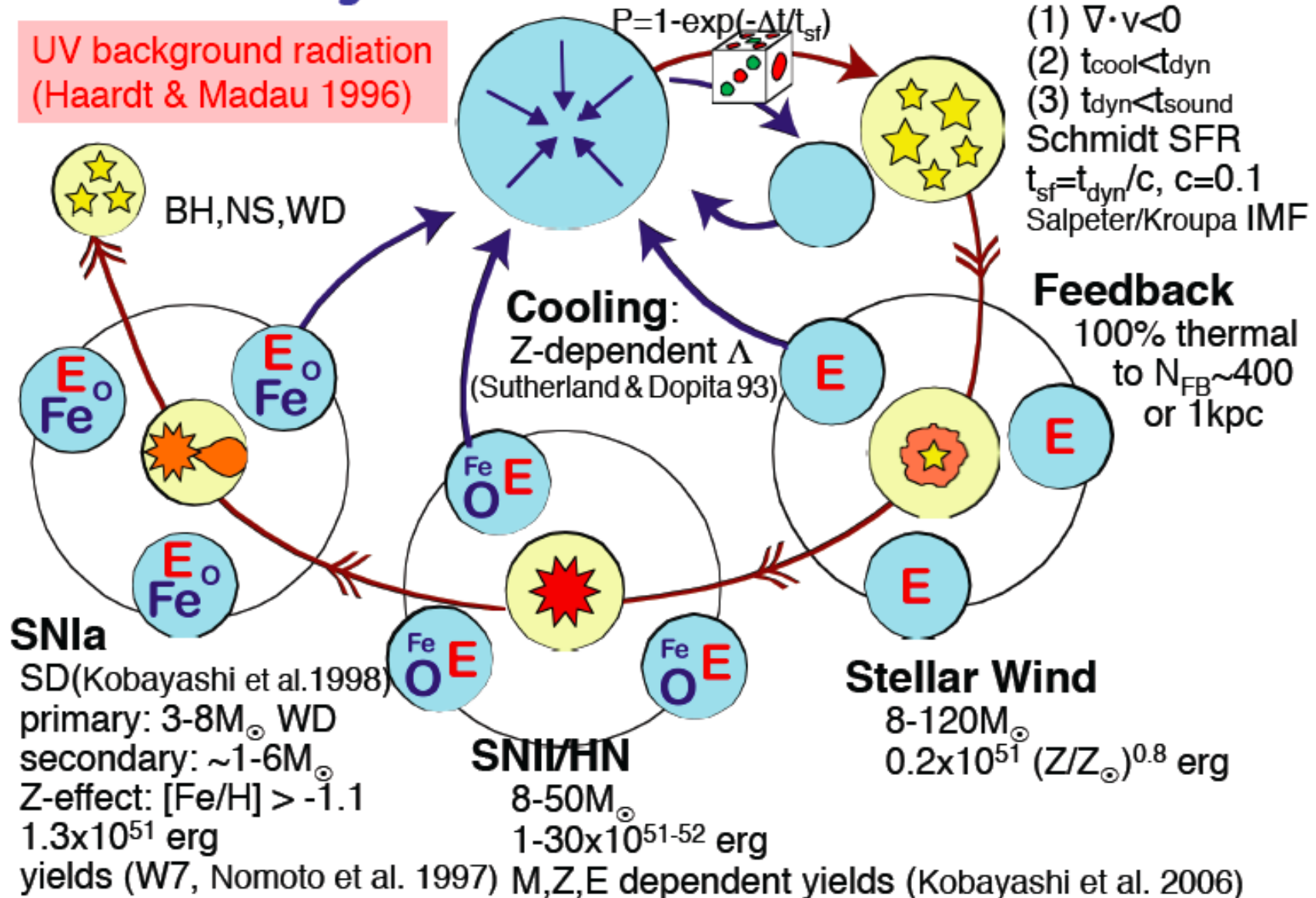
- **Build a Description from Modules for these Processes**

👉 **Francesca Matteucci, Nikos Prantzos, Chiaki Kobayashi, et al.**

# Describing Compositional Evolution Chemodynamics

Courtesy C. Kobayashi 2013

UV background radiation  
(Haardt & Madau 1996)

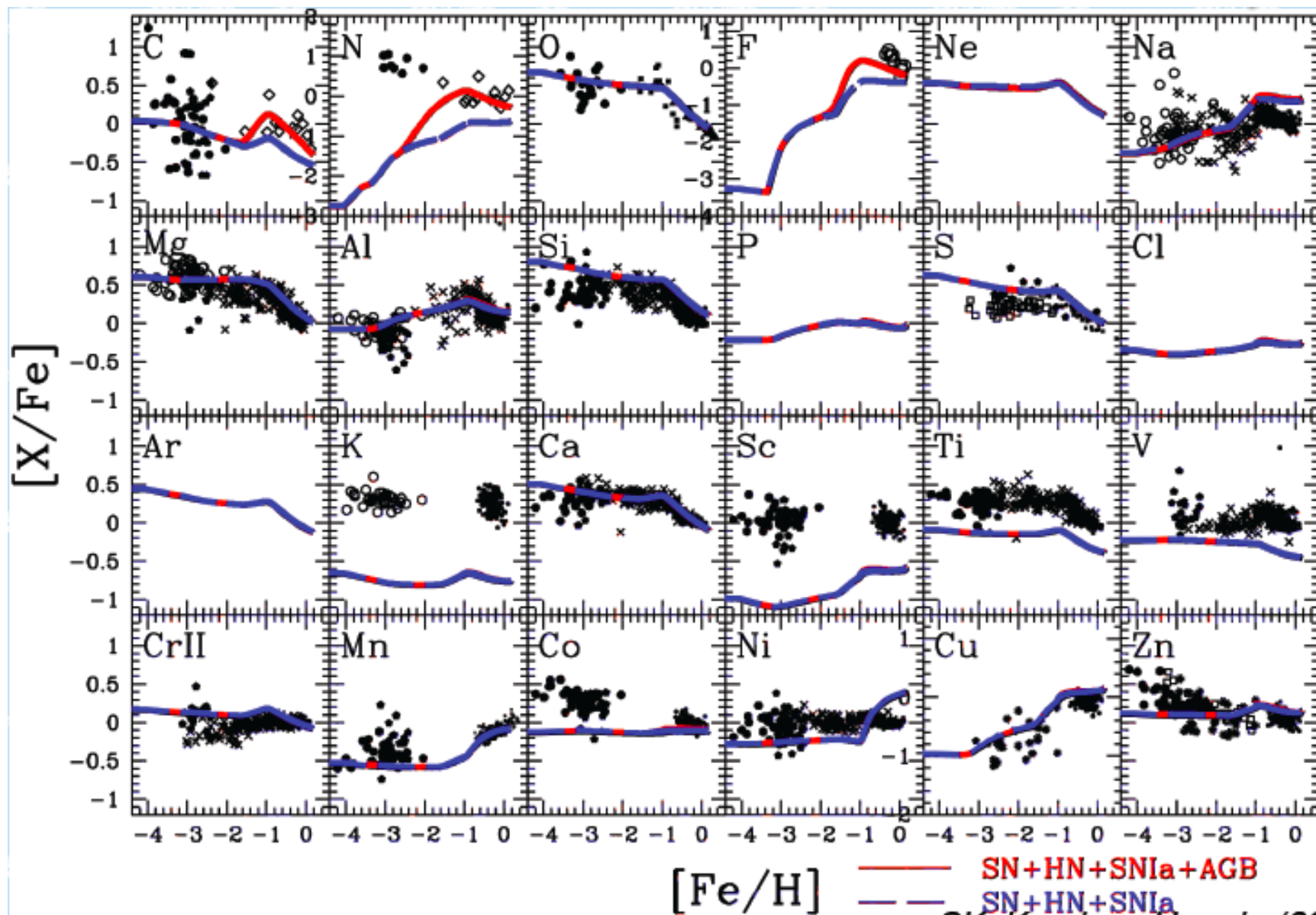




# Compositional Evolution



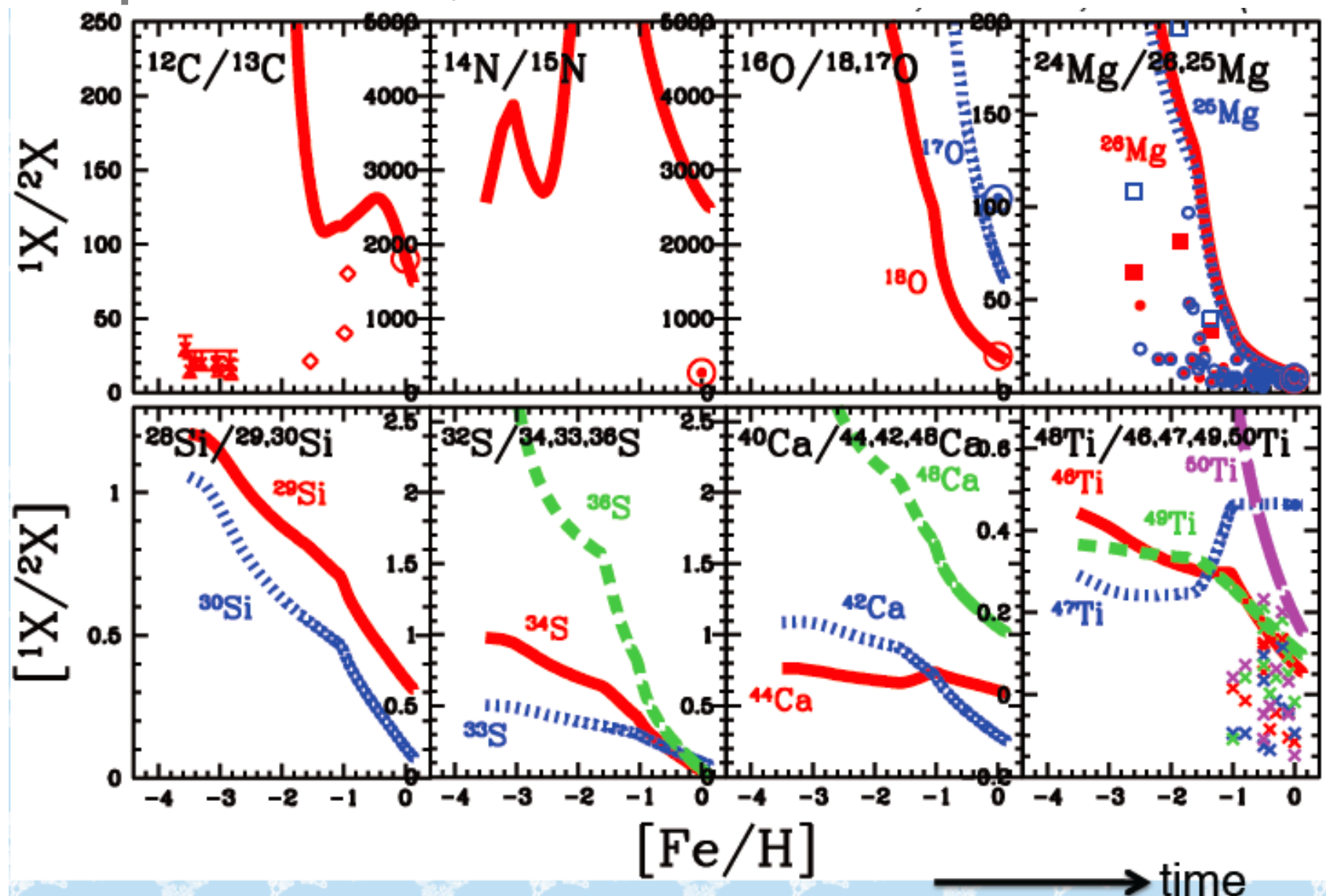
Courtesy C. Kobayashi 2013



# Compositional Evolution



- Isotopic Ratios *Kobayashi, Karakas, and Umeda 2011*



# Nucleosynthesis Sources: Open Questions



- Stars and Stellar Evolution

- Internal Mixing and Energy Transport → Structure? Burning Shells?

- Supernovae

- SN Ia: from WDs, explosive C Burning → Which Scenario??
- Core Collapses: 3D Effects

→ Which Stars Explode?

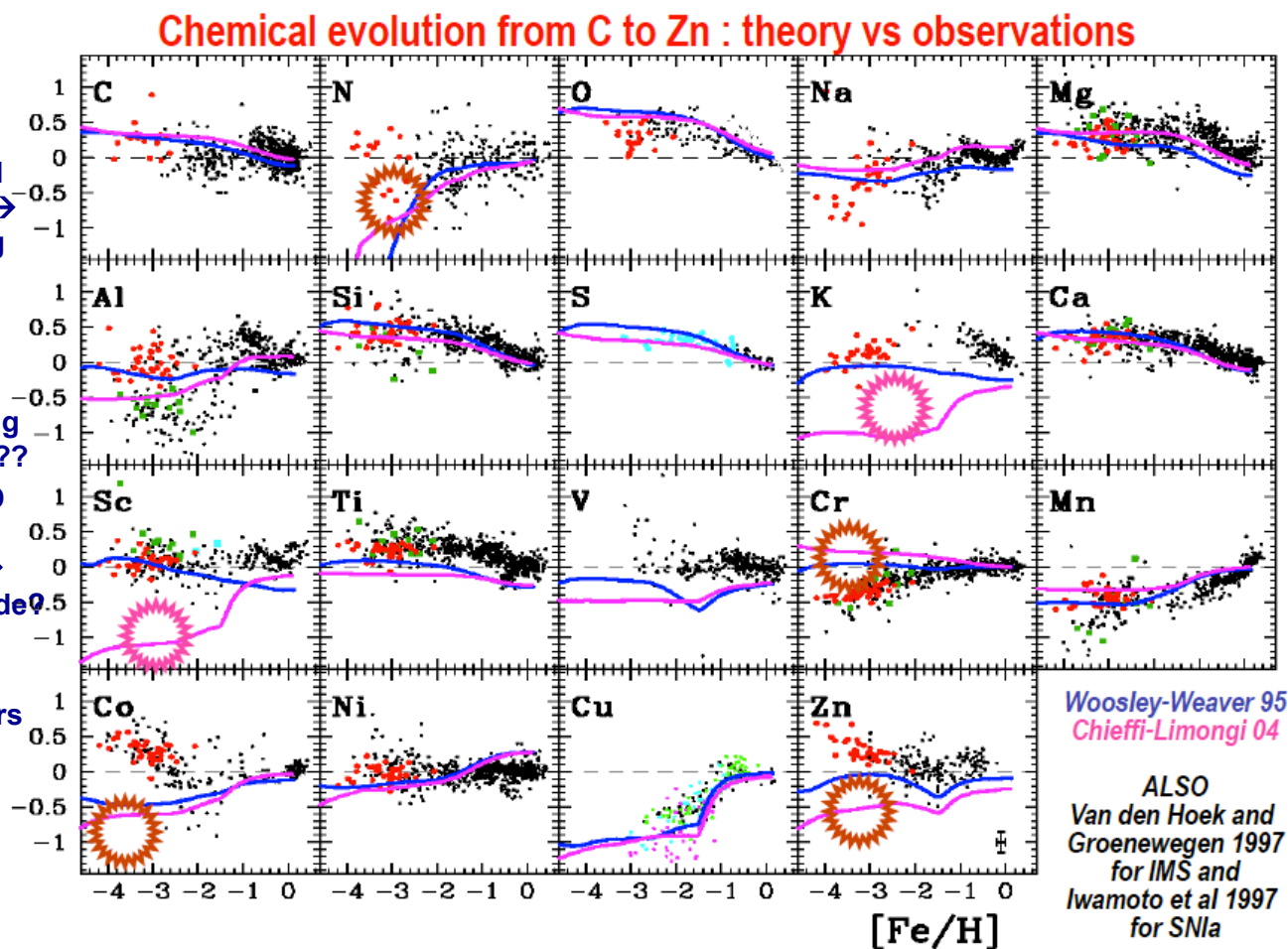
- Novae

- Accumulated Layers and Ejecta → Mixing and Burning?

- Chemical Evolution

- Inhomogeneous in Galaxies

→ Feedback, Self-Enrichment?



# Compositional Evolution: a Proxy for Time?



## ★ Accounting for Inhomogeneities in Galaxy and ISM Evolution

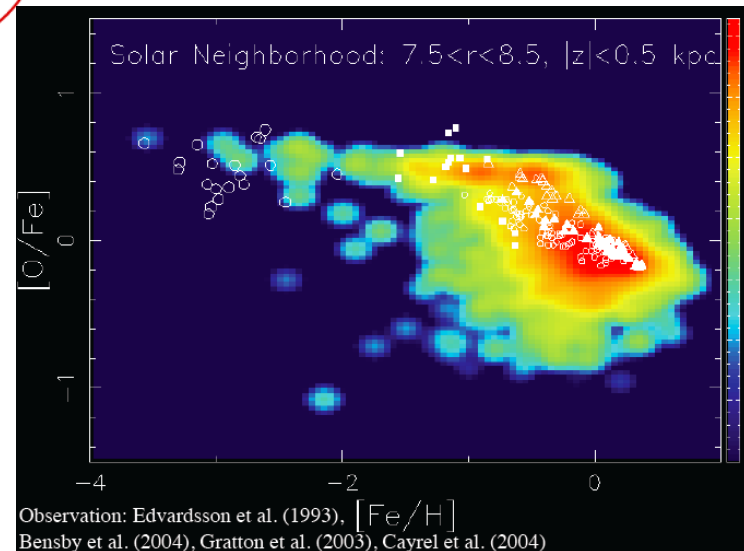
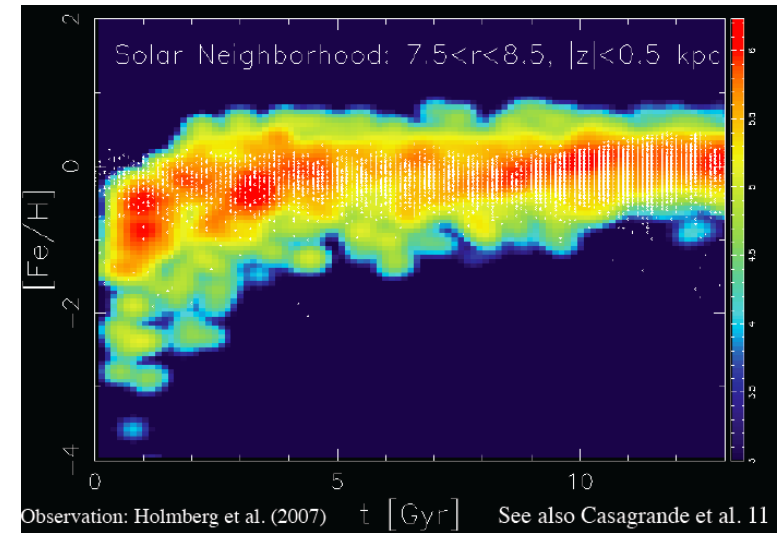
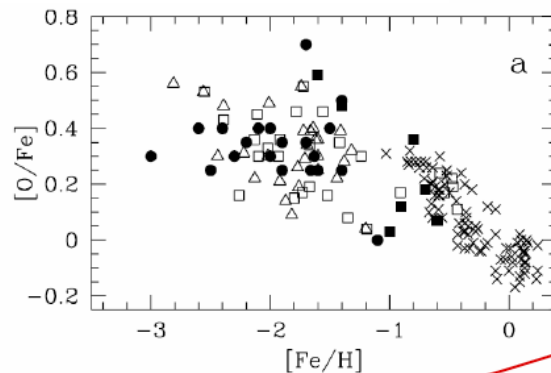
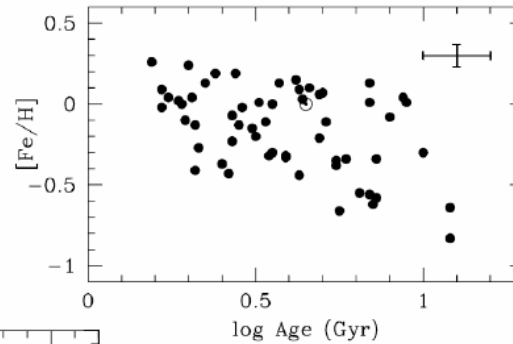
👉 “Age” / “Metallicity” Relation washed out

### ★ Age/Metallicity Relation

👉 Use Metallicity as Age Indicator

» Edvardsson et al. 1993

👉 Study Abundance Patterns versus Metallicity:



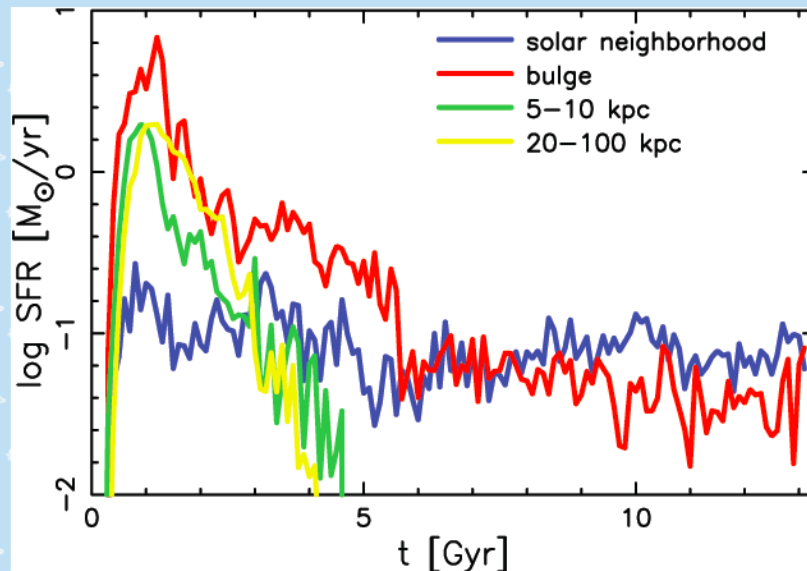


# Compositional Evolution

## ★ Accounting for Inhomogeneities in Galaxy and ISM Evolution

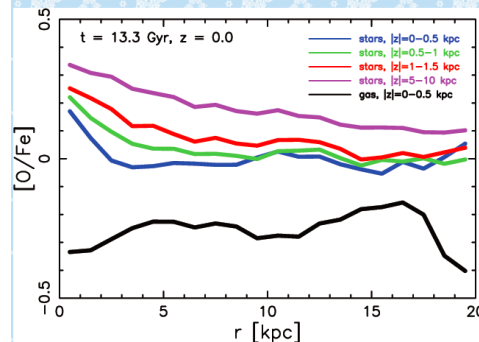
### Star Formation History depends on environment

Bulge  $r < 1$ , Solar Neighborhood:  $7.5 < r < 8.5, |z| < 0.5$  kpc



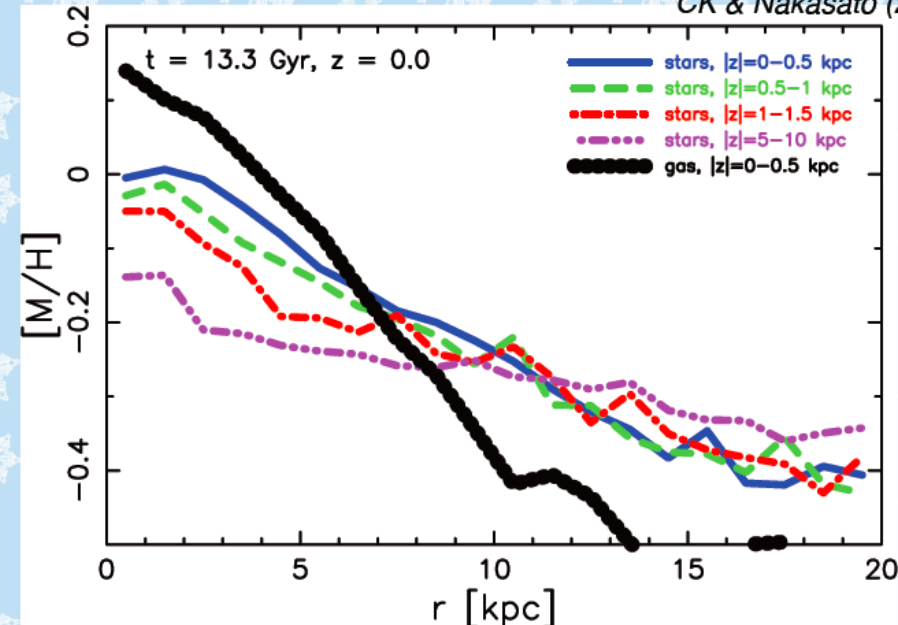
CK & Nakasato

### No $[\alpha/\text{Fe}]$ Gradients in disks



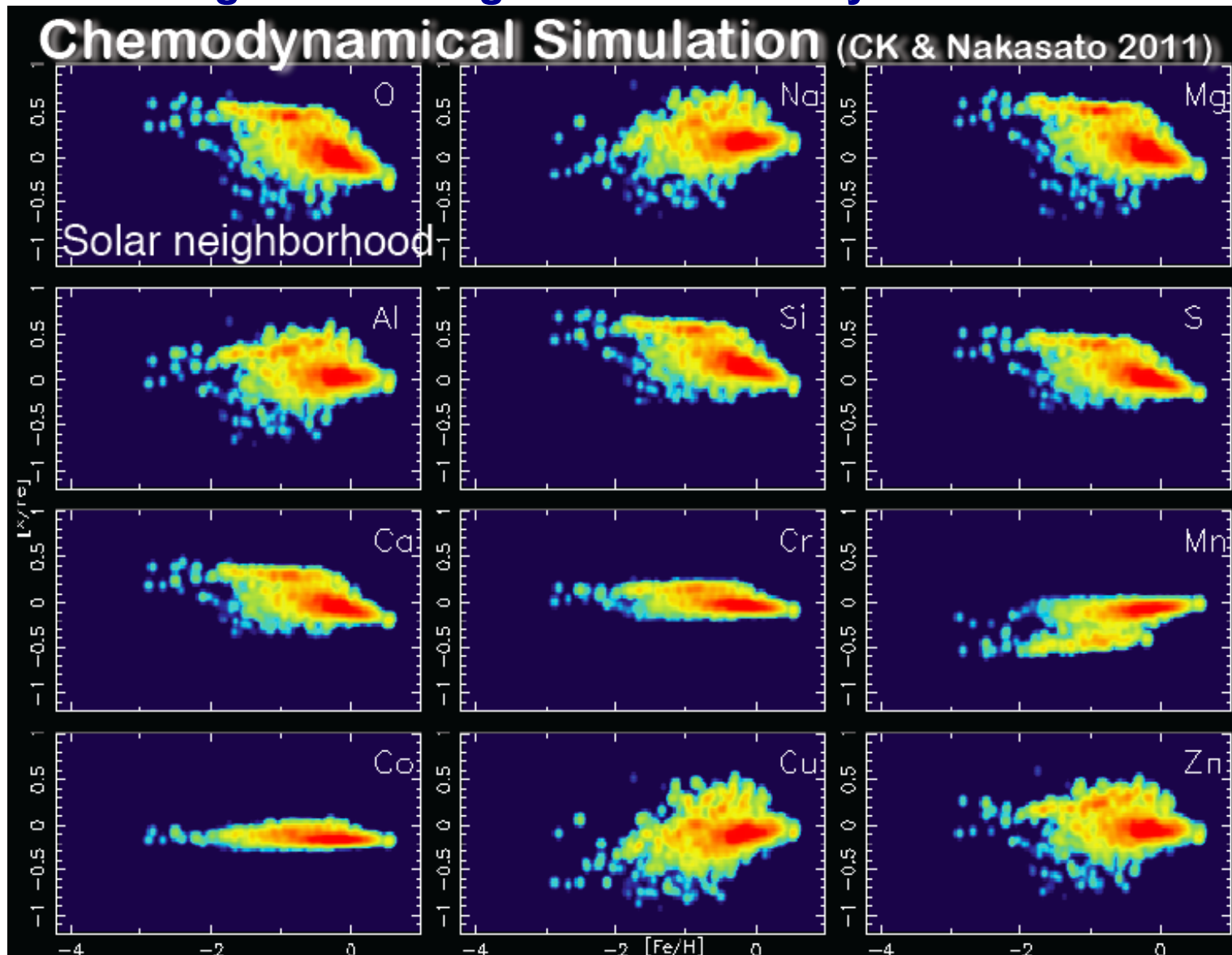
### Metallicity Gradients @ $z=0$

CK & Nakasato (2011)



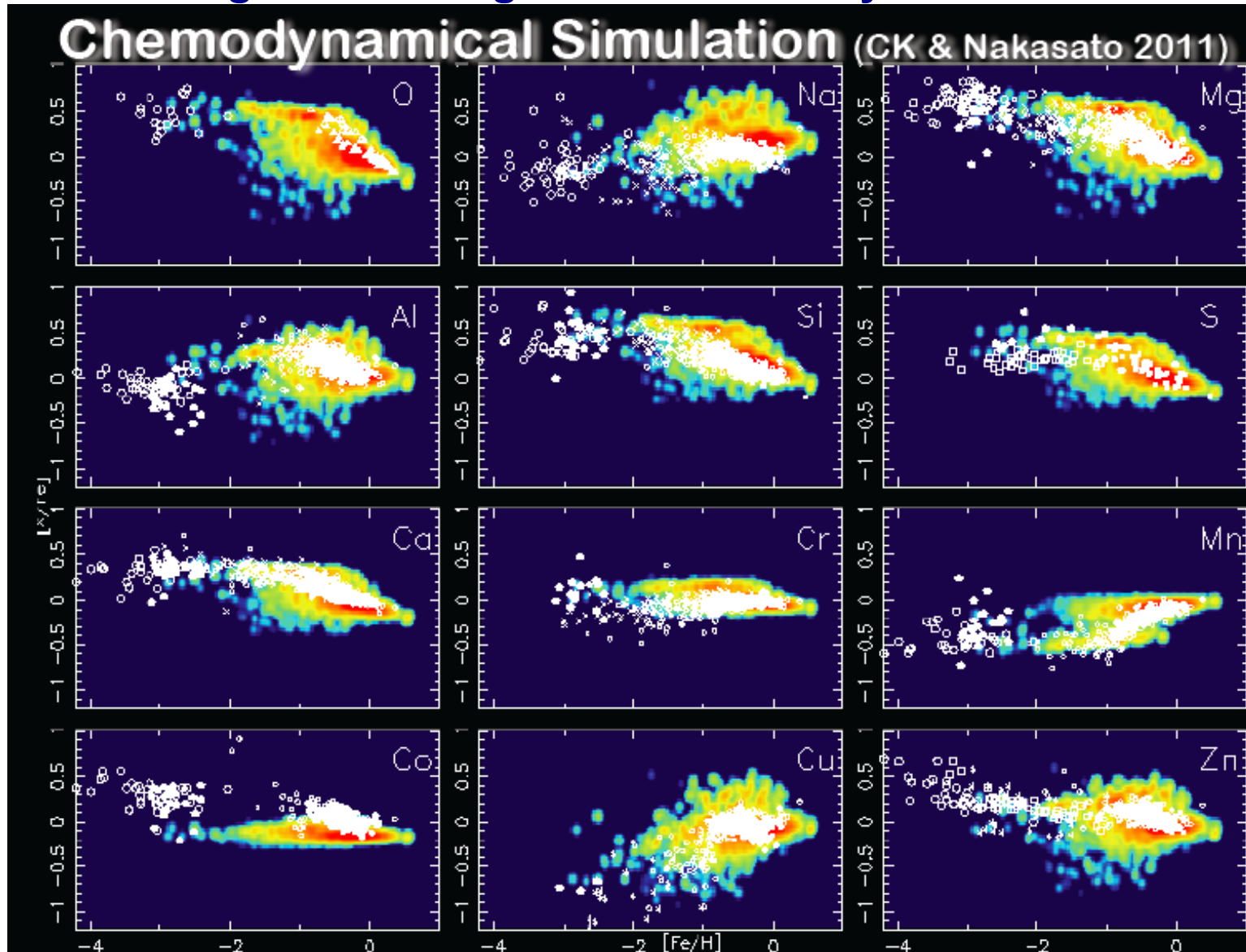
# Compositional Evolution

## ★ Accounting for Inhomogeneities in Galaxy and ISM Evolution



# Compositional Evolution

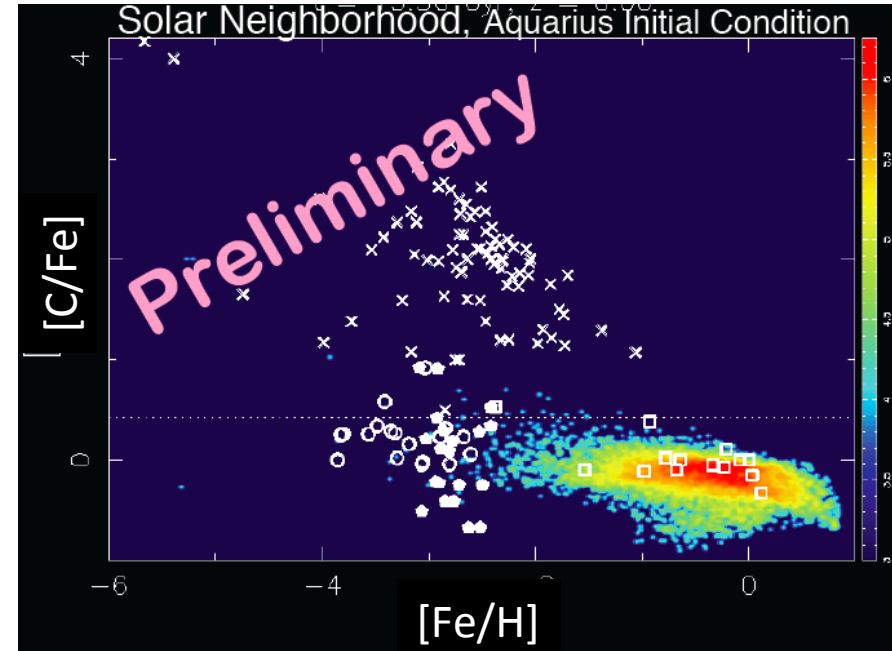
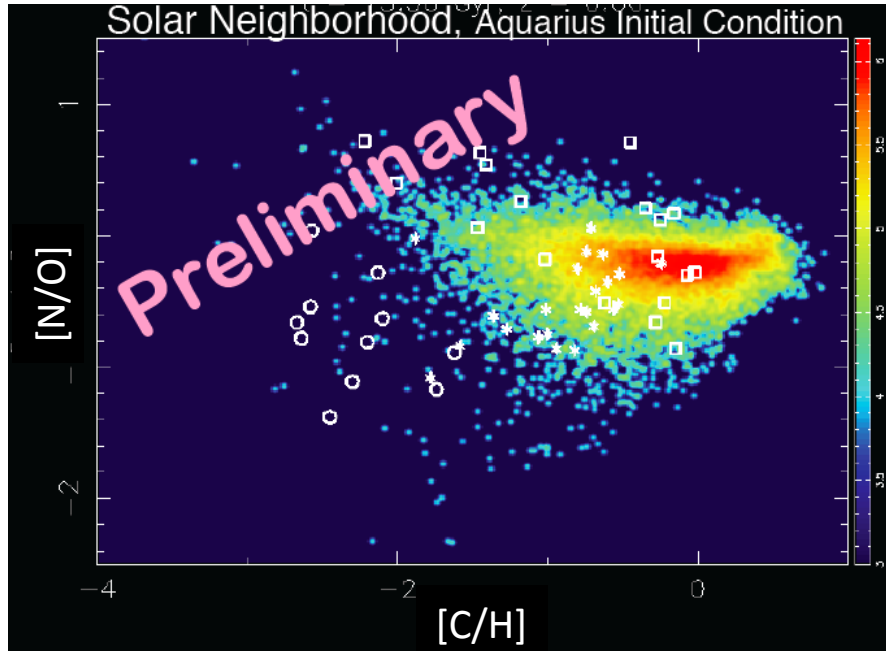
## ★ Accounting for Inhomogeneities in Galaxy and ISM Evolution



# Compositional Evolution: Element Ratios

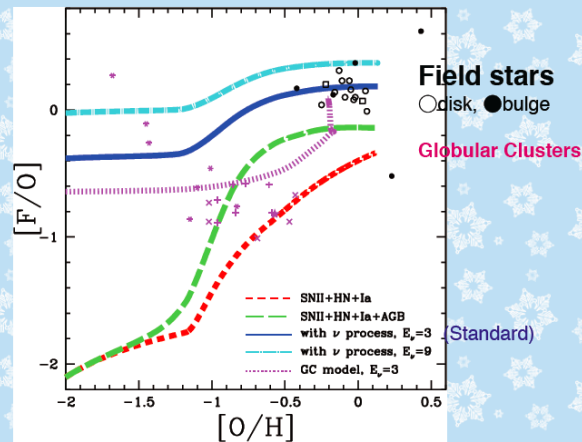
Courtesy C. Kobayashi 2013

## ★ Accounting for Inhomogeneities in Galaxy and ISM Evolution

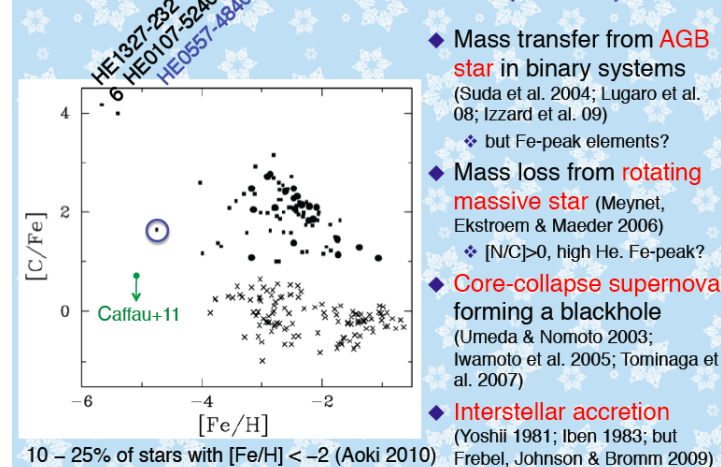


### Fluorine problem – the $\nu$ process?

CK, Izutani, Karakas, T.Yoshida, Yong, Umeda 2011, ApJL

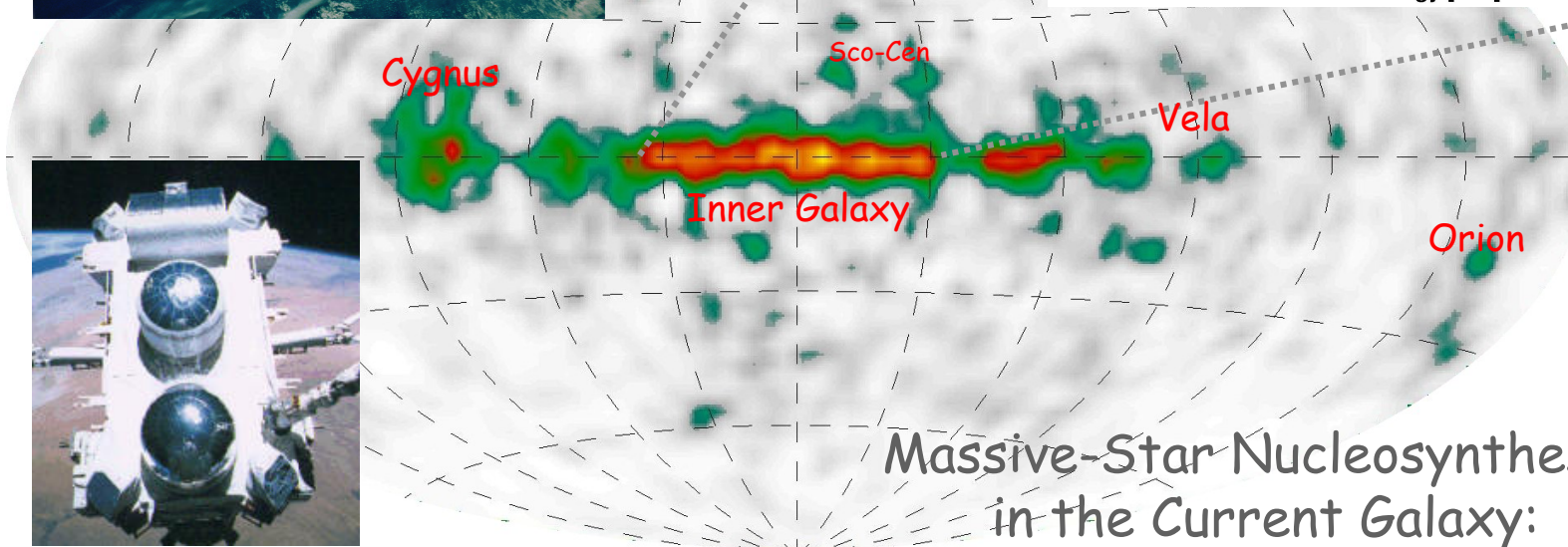
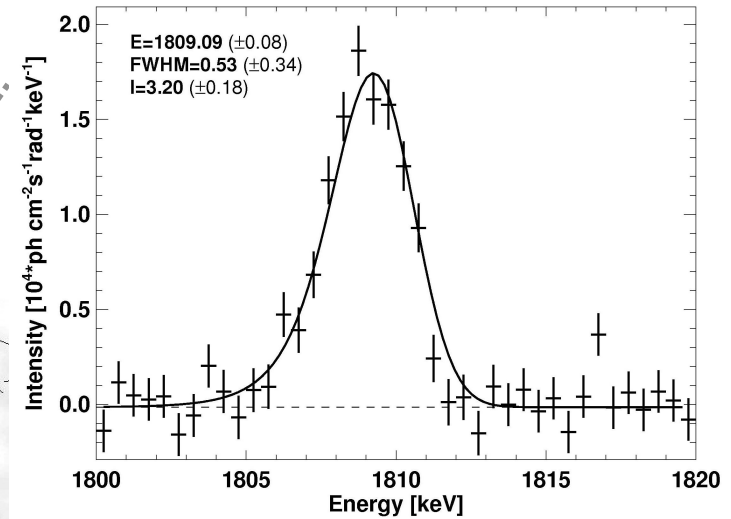


### Carbon-Enhanced Metal Poor (CEMP) Stars





# $^{26}\text{Al}$ in our Galaxy: g-ray Image and Spectrum



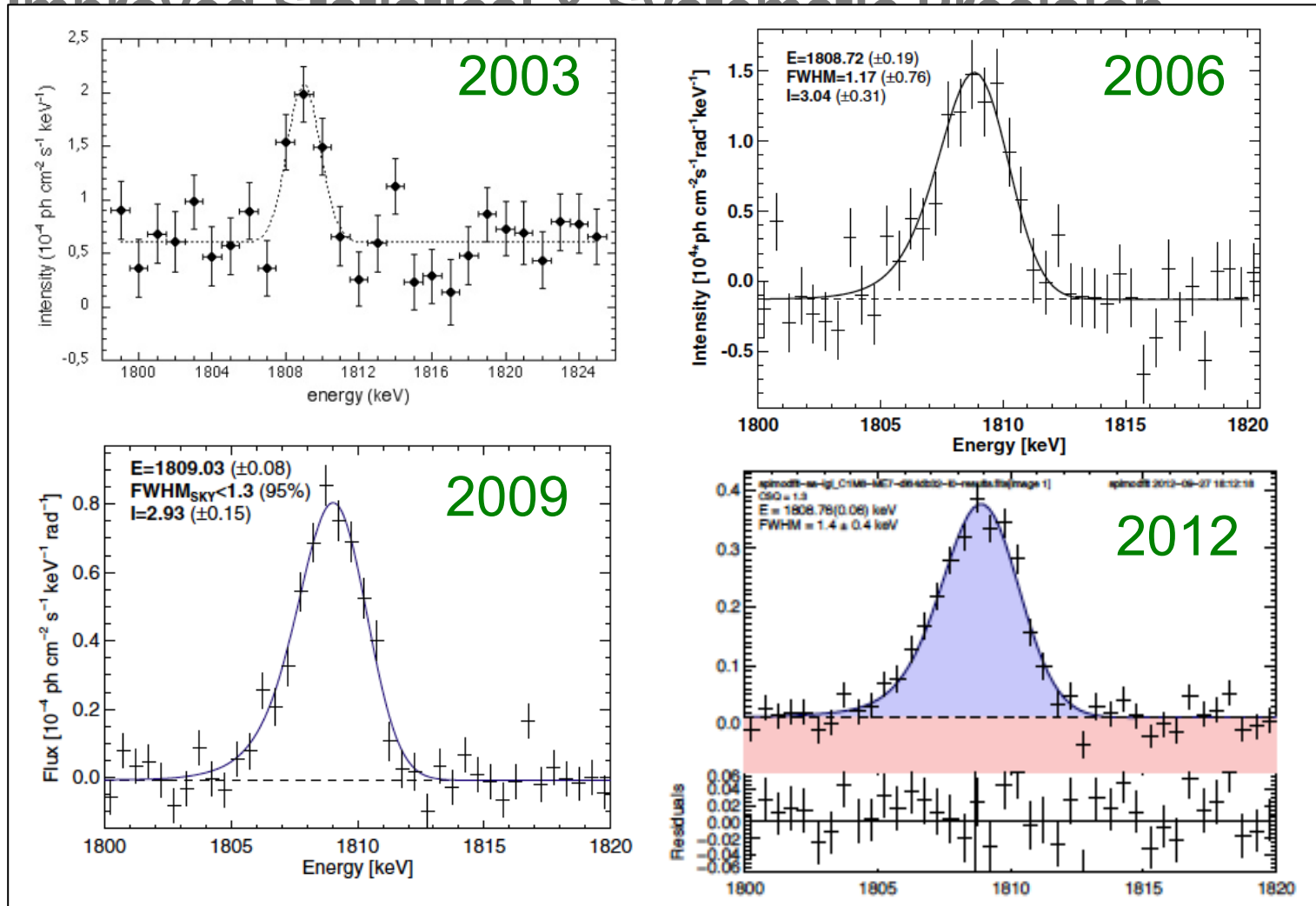
Massive-Star Nucleosynthesis  
in the Current Galaxy:  
Exploiting the Message from  $^{26}\text{Al}$  g-rays

# Measuring the $^{26}\text{Al}$ Gamma-Ray Line from the Galaxy



- Increasing Exposure (Oct 2002.... Today)

→ Improved Statistical & Systematic Precision

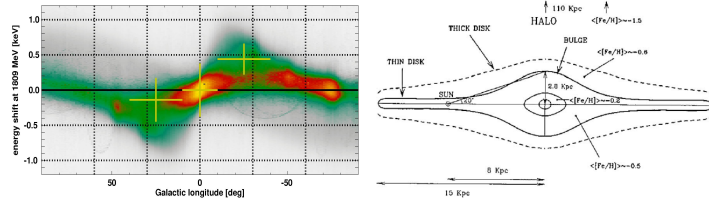


# Using the $^{26}\text{Al}$ Line to Characterize the Galaxy



- ★ Measured Gamma-Ray Flux
- ★ Galaxy Geometry

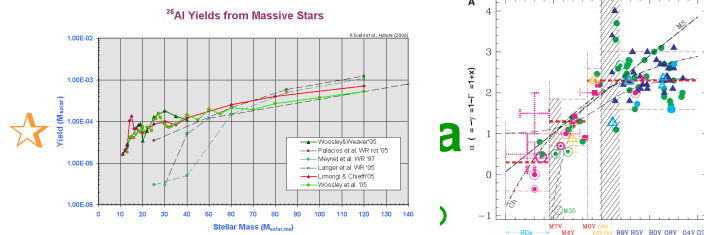
➤  $^{26}\text{Al}$  Mass in Galaxy  
 $= 2.25 (\pm 0.65) M_{\odot}$



- ★  $^{26}\text{Al}$  Yields per Star
- ★ Stellar Mass Distribution

✓ cc-SN Rate =  $1.5 (\pm 0.9)$  per Century

✓ SFR =  $3.1 M_{\odot}/\text{yr}$



✓ Al Isotopic Ratio =  $6 \cdot 10^{-6}$

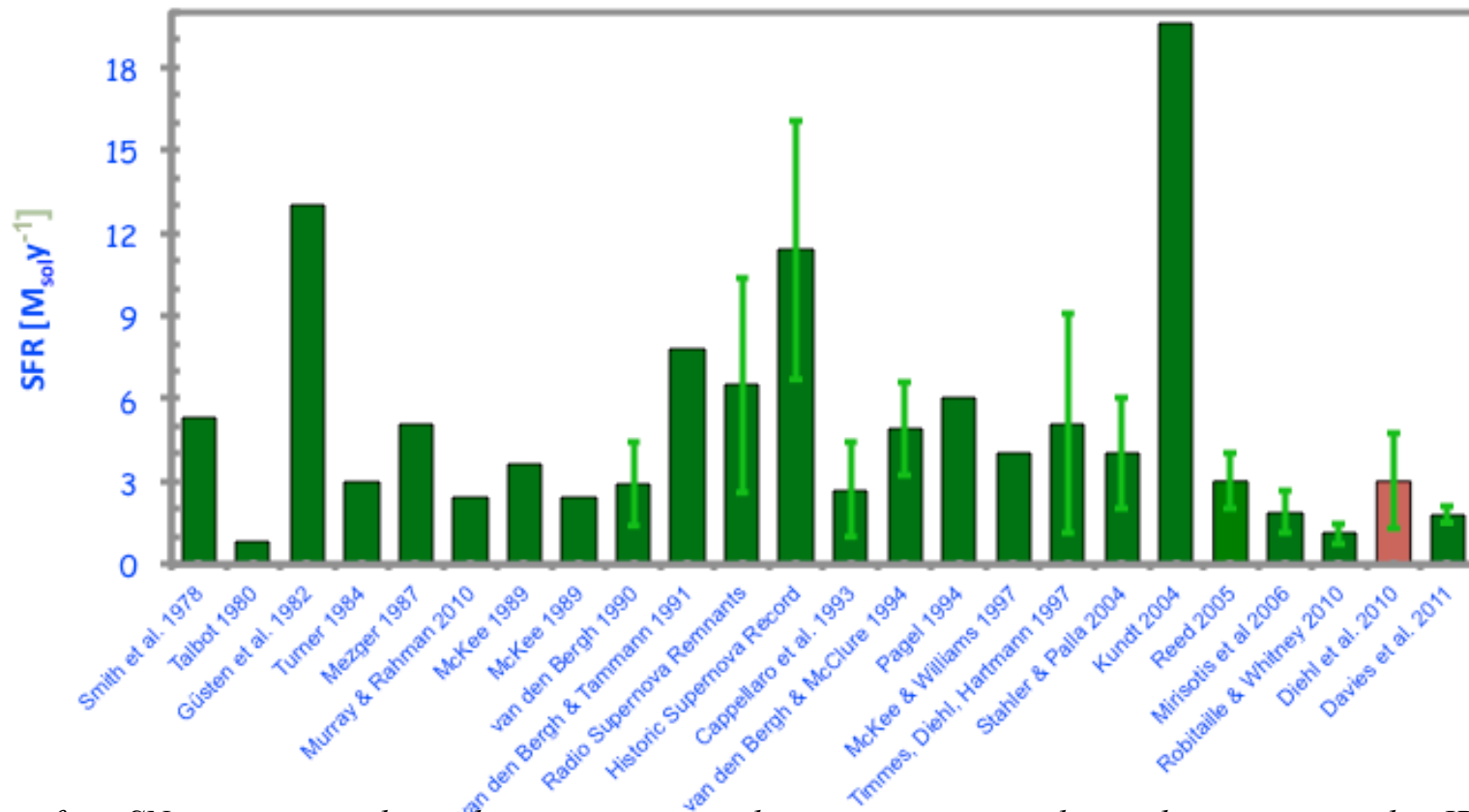
# The Galactic Star Formation Rate

👉 **Overall Rate  $\sim 2.3 \text{ M}_{\odot}/\text{yr}$  ( $1.9 \pm 0.4 \text{ M}_{\odot}/\text{yr}$ , Chomiuk & Povich 2012)**

» Various methods, different biases

» *Extragalactic/galactic; sampling region; IMF; models*

Roland Diehl 2013



...from SN statistics in other galaxies; ionization; dust; star counts; nucleosynthesis – opt...radio..IR..g-rays



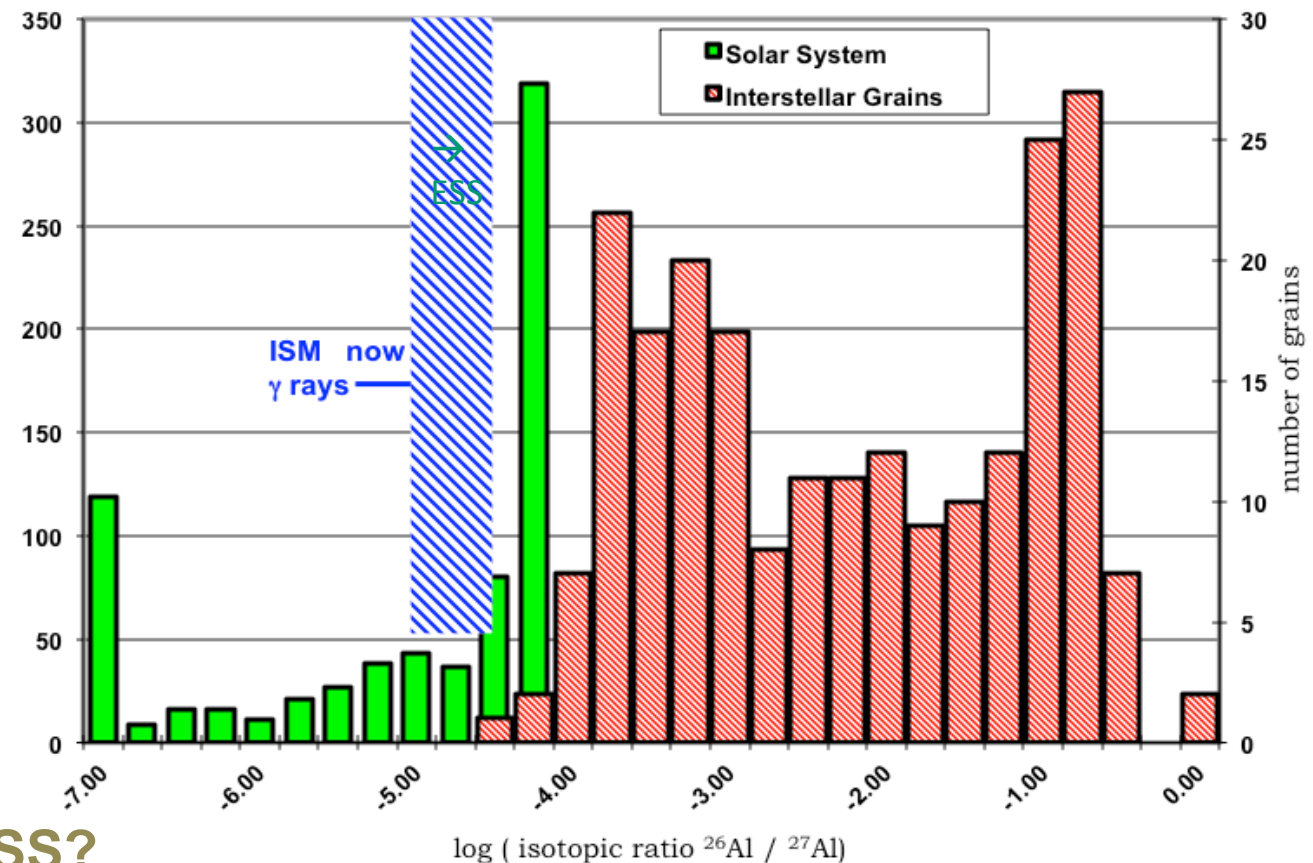
# The $^{26}\text{Al}/^{27}\text{Al}$ Isotope Ratio

★ **Current ISM Value Measured from  $\gamma$ -Rays  $\rightarrow 6 \cdot 10^{-6}$**

👉 evolution  $^{27}\text{Al} \sim t^2$  (secondary isotope),  $^{26}\text{Al}$  steady  $\rightarrow 1.5 \cdot 10^{-5}$  in ISM at ESS

★ **Compare to Meteoritic (=ESS) and Presolar-Grain (sources) values**

👉 **ESS Meteorites:  $5.2 \cdot 10^{-5}$**

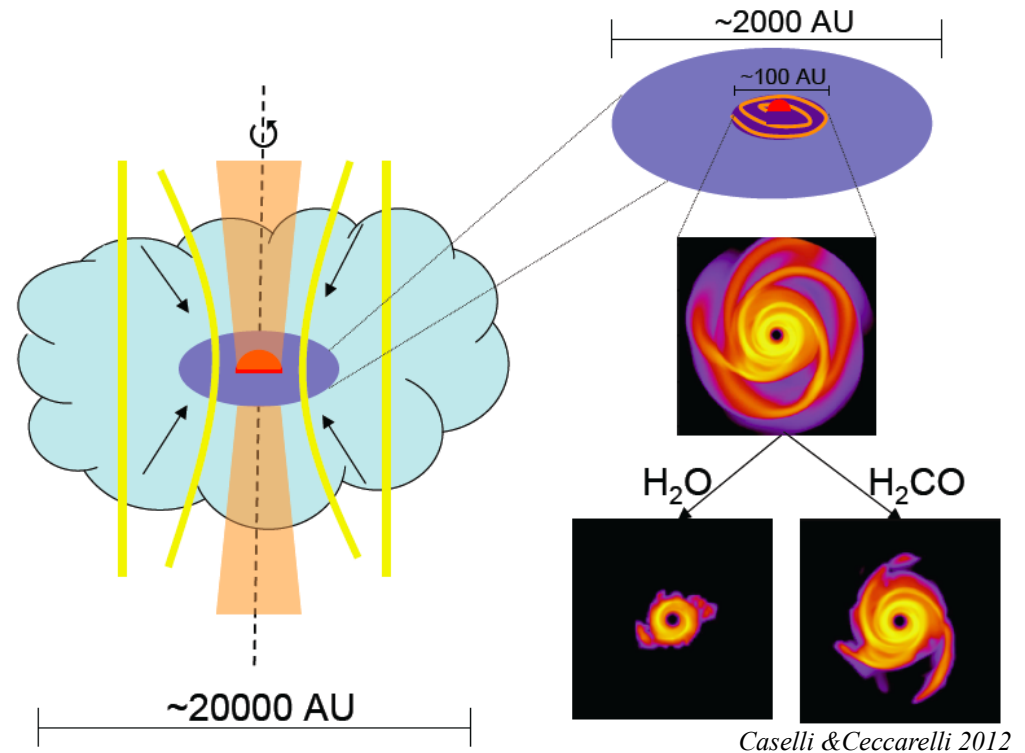
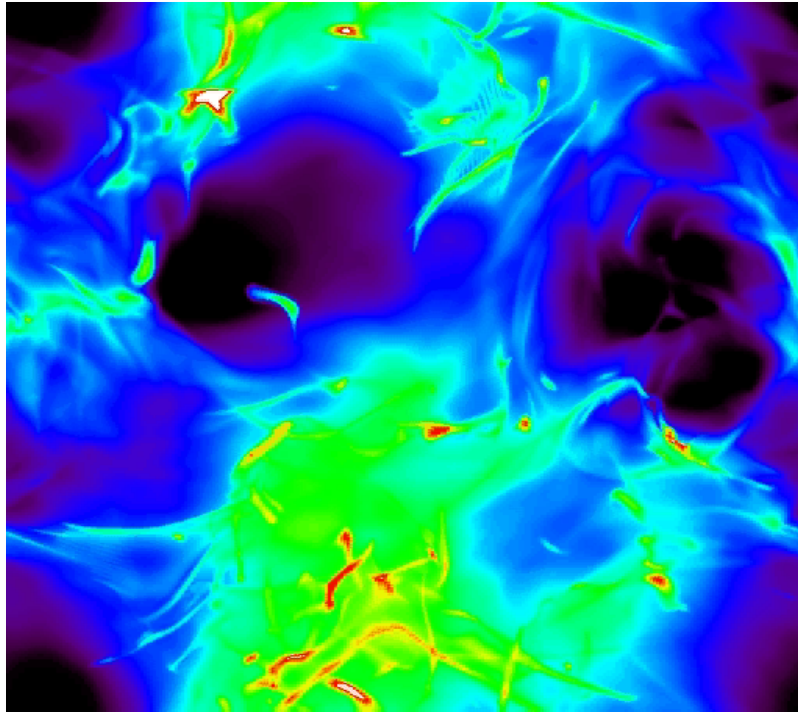


★ **Enrichment of ESS?**

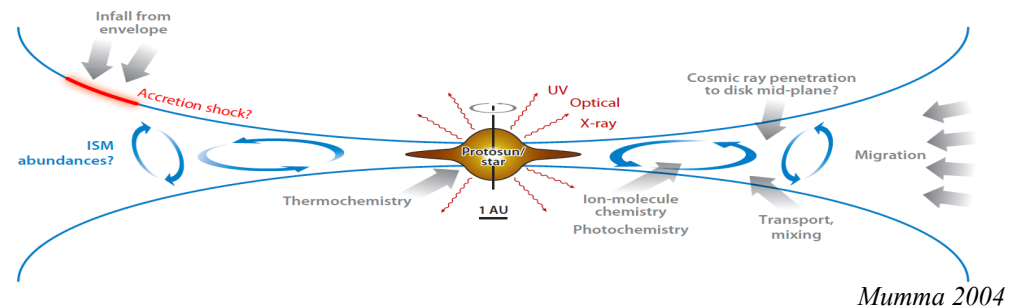
# ISM transport towards a newly-forming star/Sun



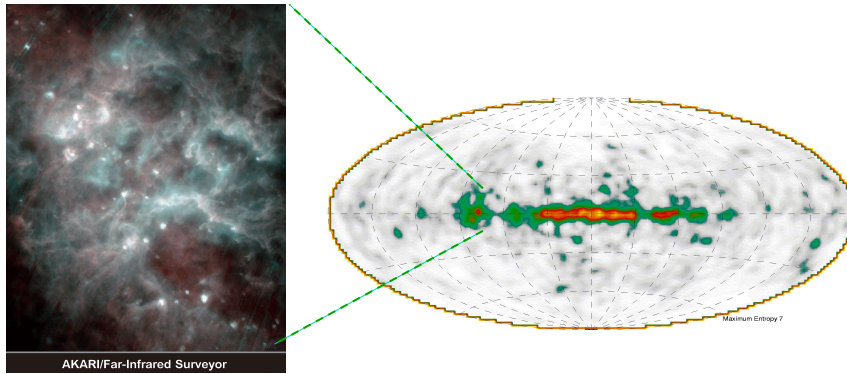
Vasileiadisi 2013



- From a dynamic ISM a concentration of gas cools → protostar
- ISM ingestion through rapid disk flow
- Accreting ISM partly forms solids at inner disk edge



# Testing our Models: Cygnus at its Specific Age

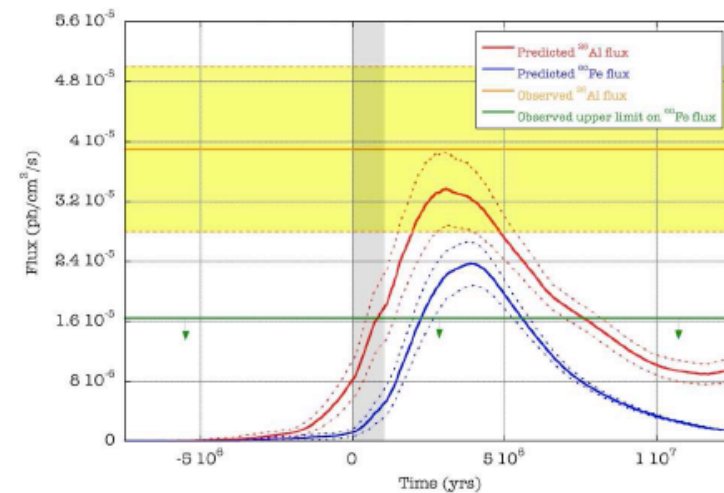
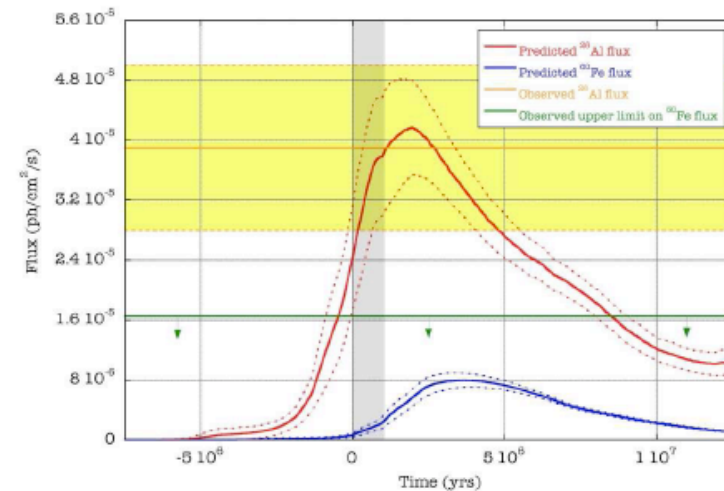
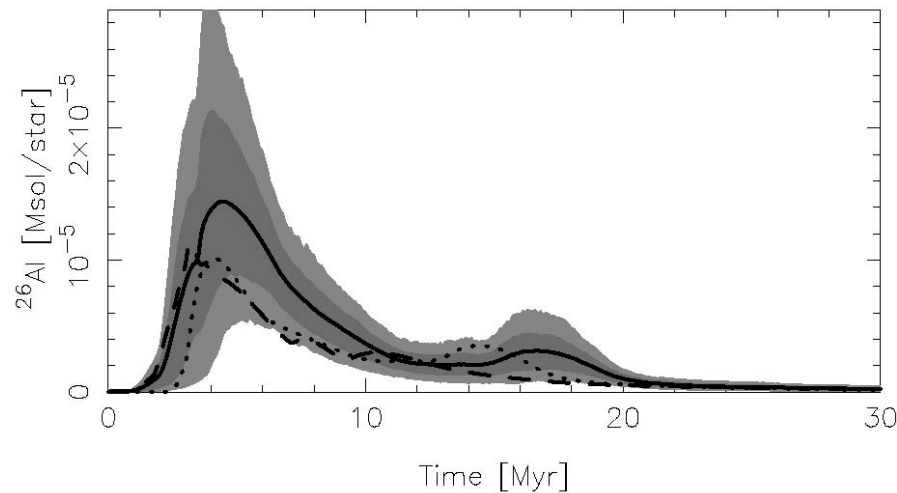


## ★ Population Synthesis: Application to Cygnus Region

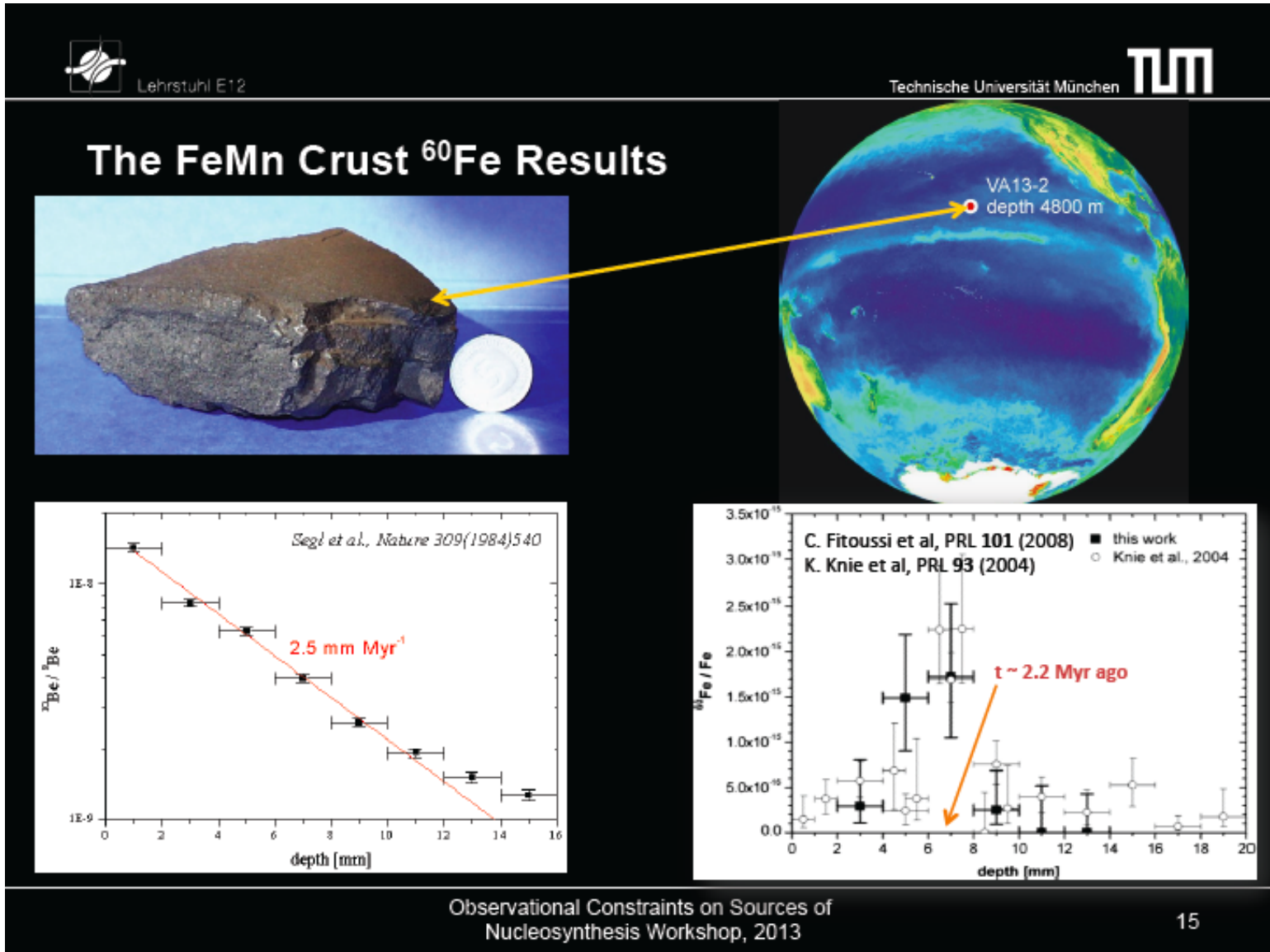
👉 Models for Solar Metallicity ~OK

👉 If Lower Metallicity:  
Underprediction?

👉 Martin+ 2010



# AMS Measurements of $^{60}\text{Fe}$ on Earth





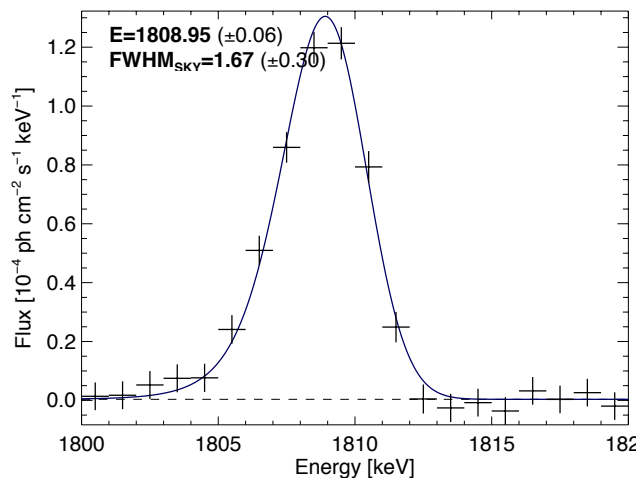
# Measuring the $^{26}\text{Al}$ Gamma-Ray Line in Detail



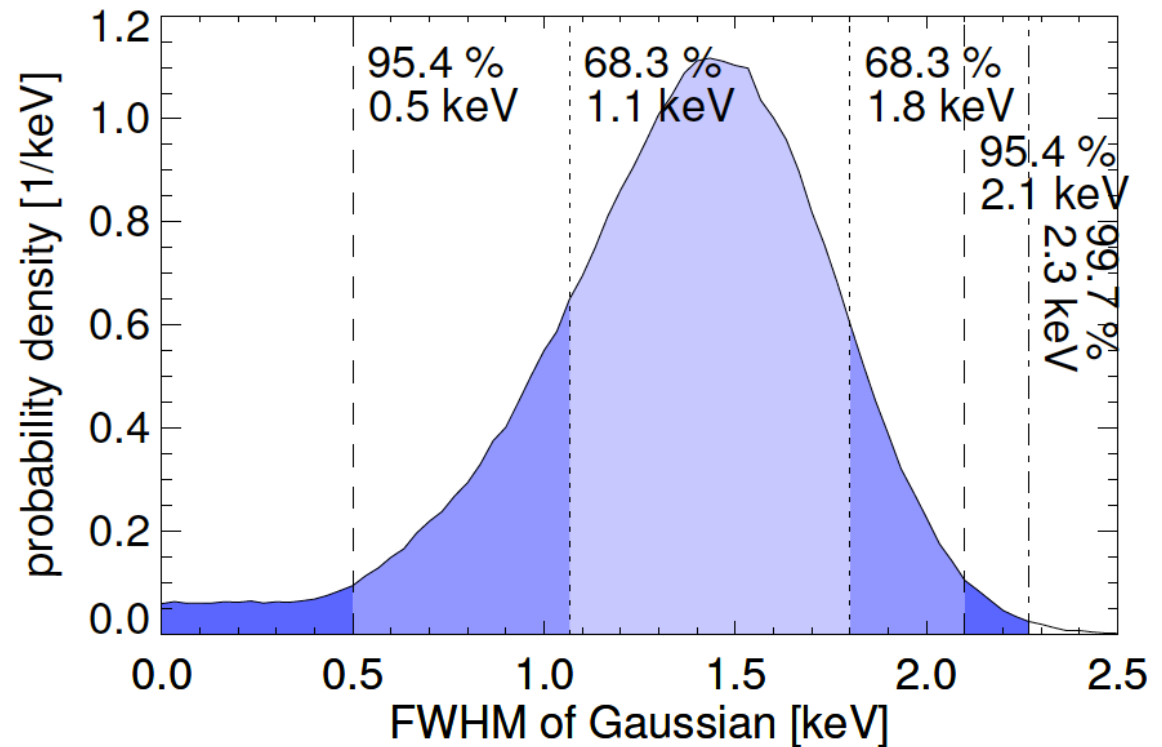
- Line Width:

- ★ Account for Instrumental Line Width ( $\sim 3$  keV)

- ★ Extract Additional (astrophysical) Broadening  $\rightarrow$  Doppler velocity



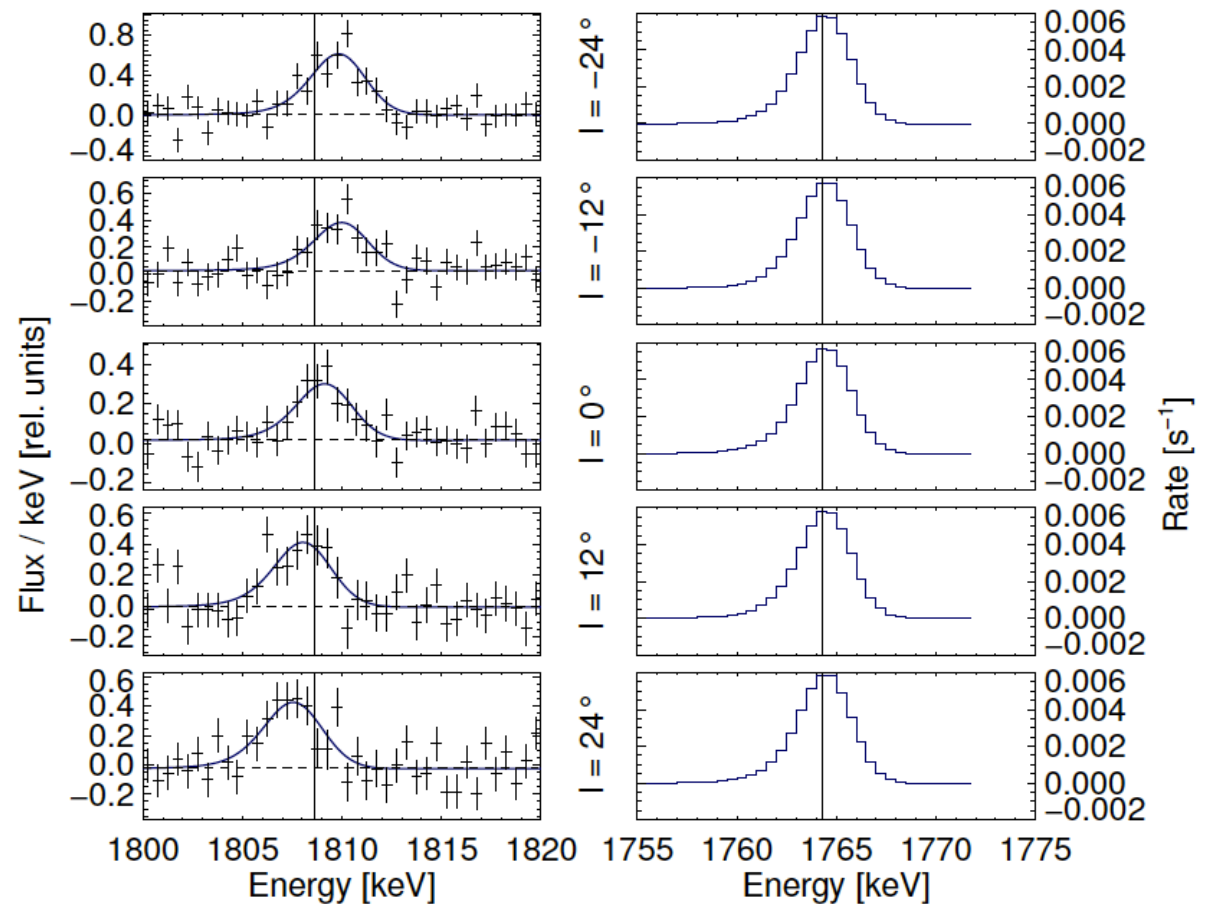
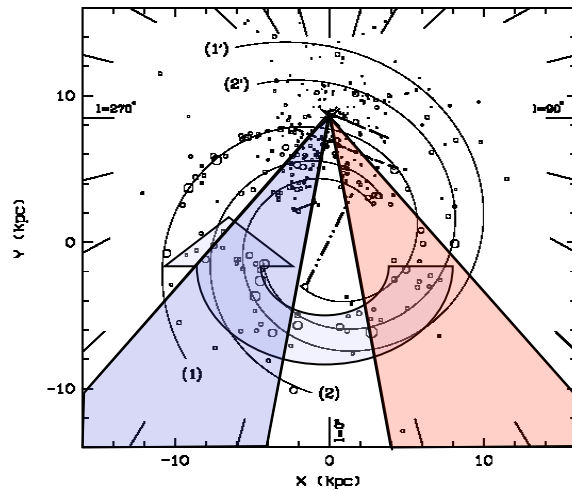
☞  $\sim 1.4 \pm 0.35 \pm 0.3$  keV  
 Consistent with  
 Expectation  
 from Galactic  
 Rotation ( $\sim 1.35$  keV)



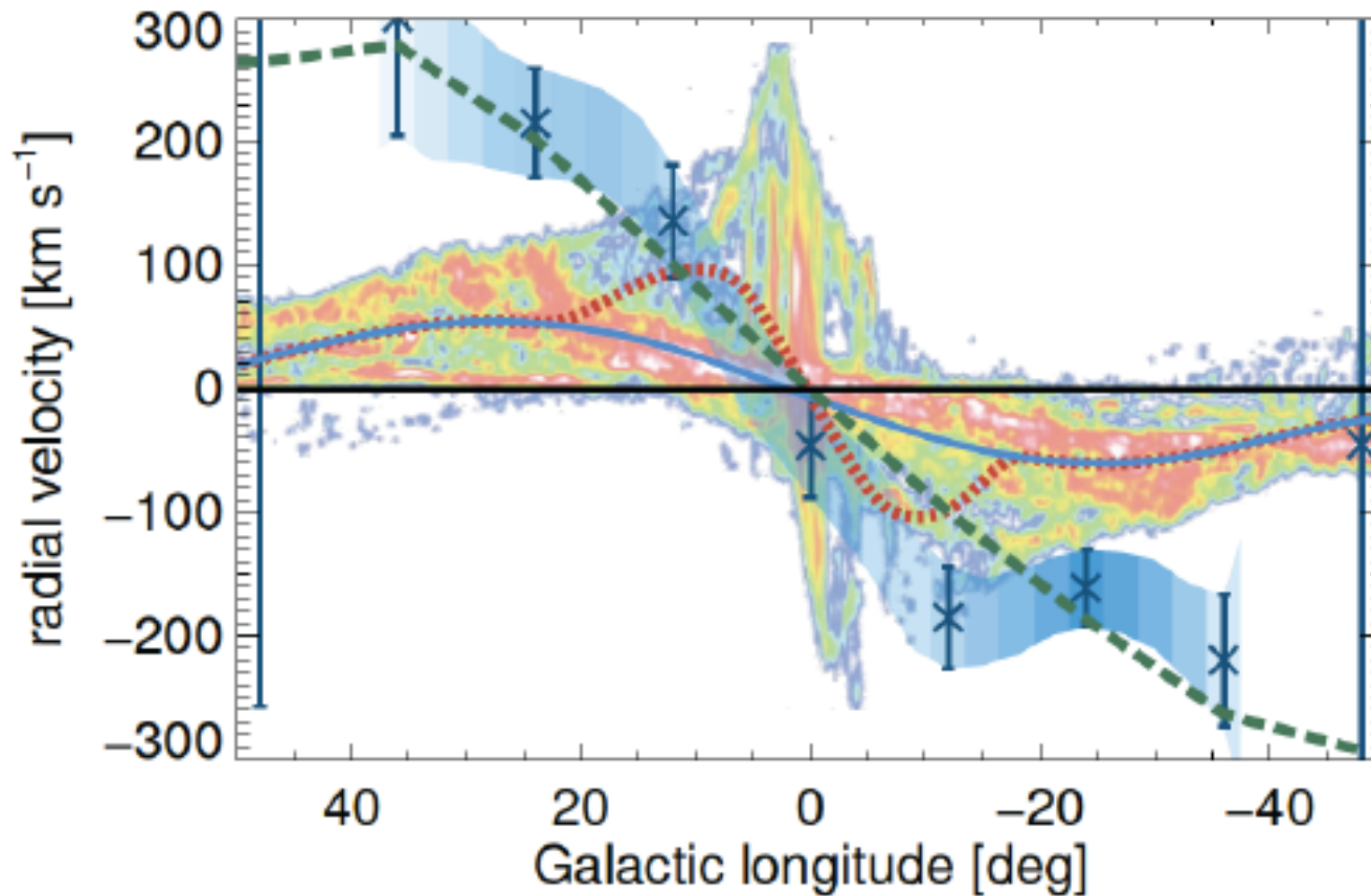
$175 \pm 45 \text{ km s}^{-1}$

# Spatially-Resolved Spectroscopy

- Analyze Line Shape and Position for Different Directions
  - ★ Galactic Rotation



# $^{26}\text{Al}$ in the Inner Galaxy: Excess Gas Velocities Seen in $^{26}\text{Al}$

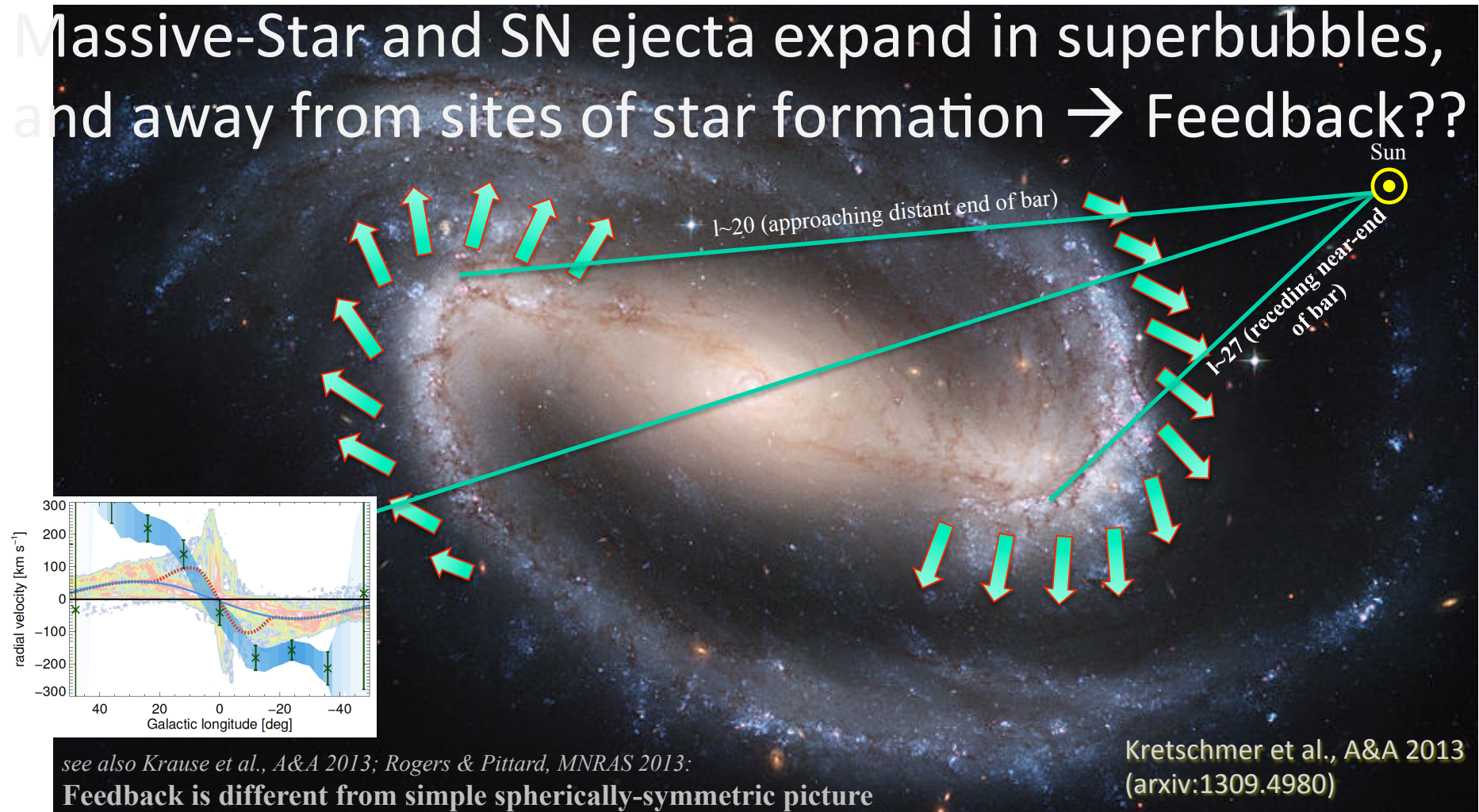


# How Massive-Star Feedback Occurs...



- $^{26}\text{Al}$  Kinematics  $\rightarrow$  Large-scale preference for outflow towards spiral-arm's leading edges

Massive-Star and SN ejecta expand in superbubbles, and away from sites of star formation  $\rightarrow$  Feedback??

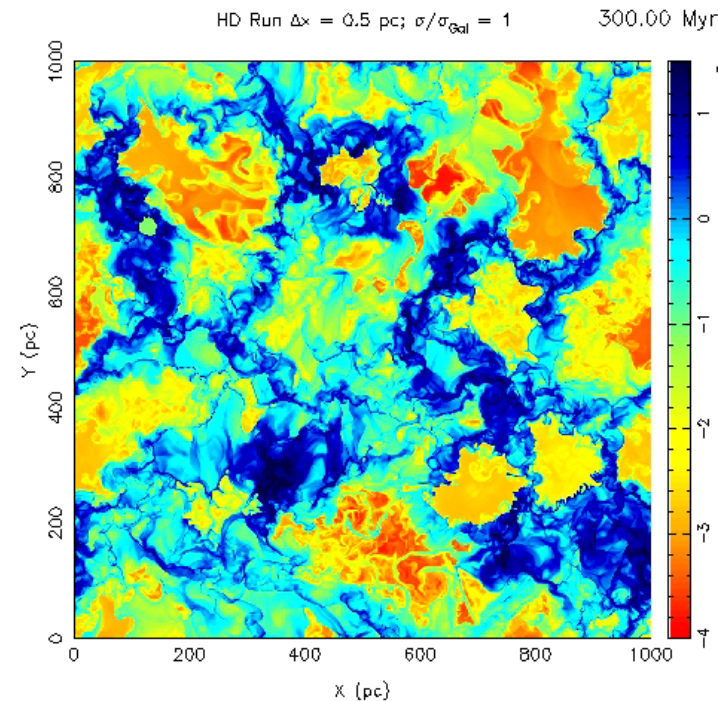
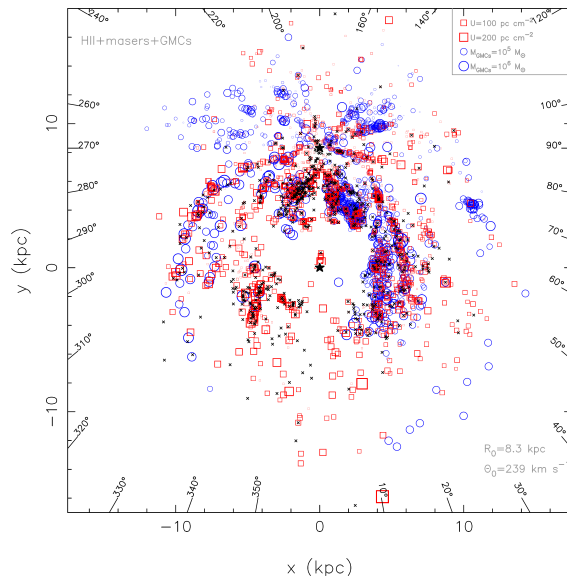
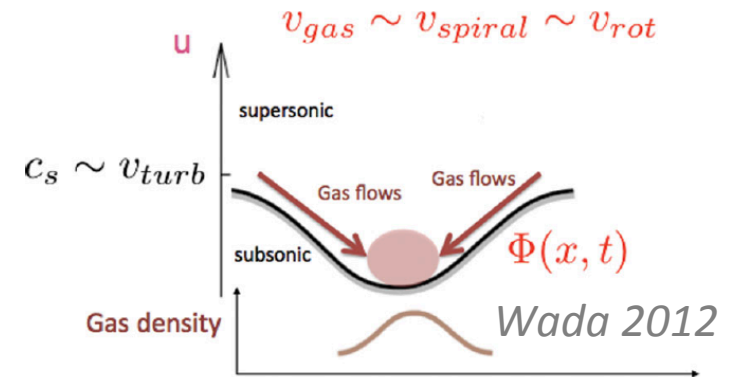




# Assist the Interpretation of Ejecta Kinematics in the Galaxy



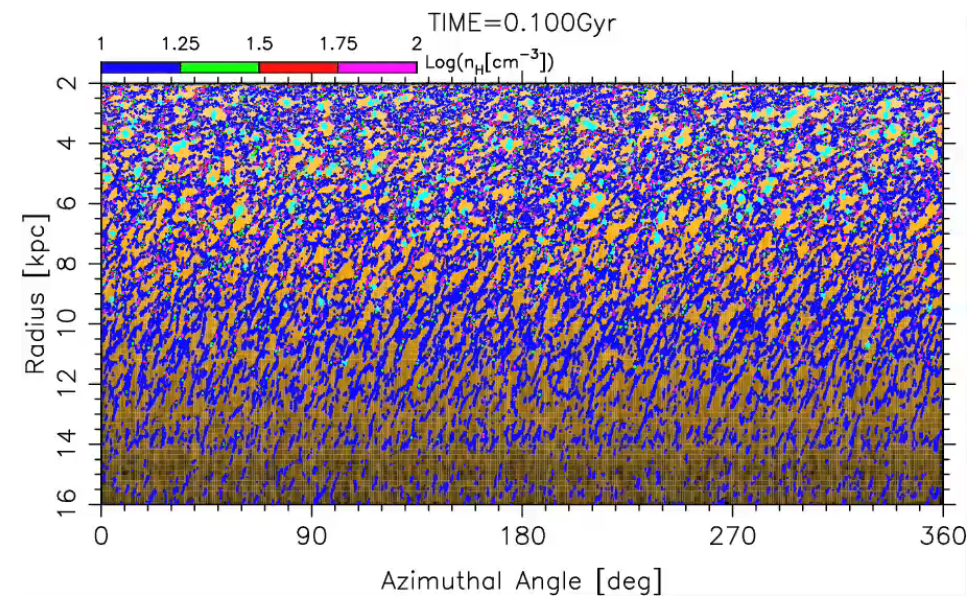
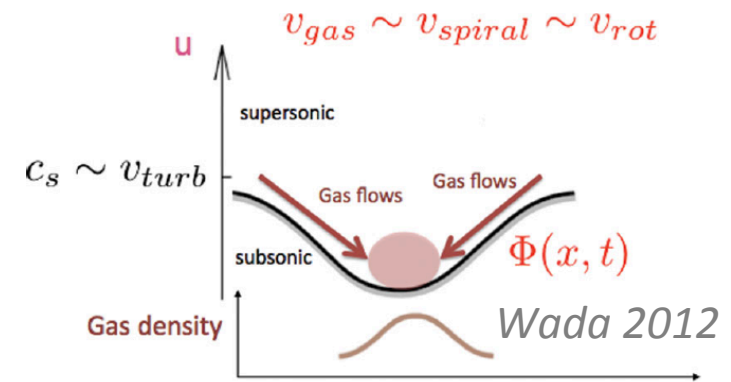
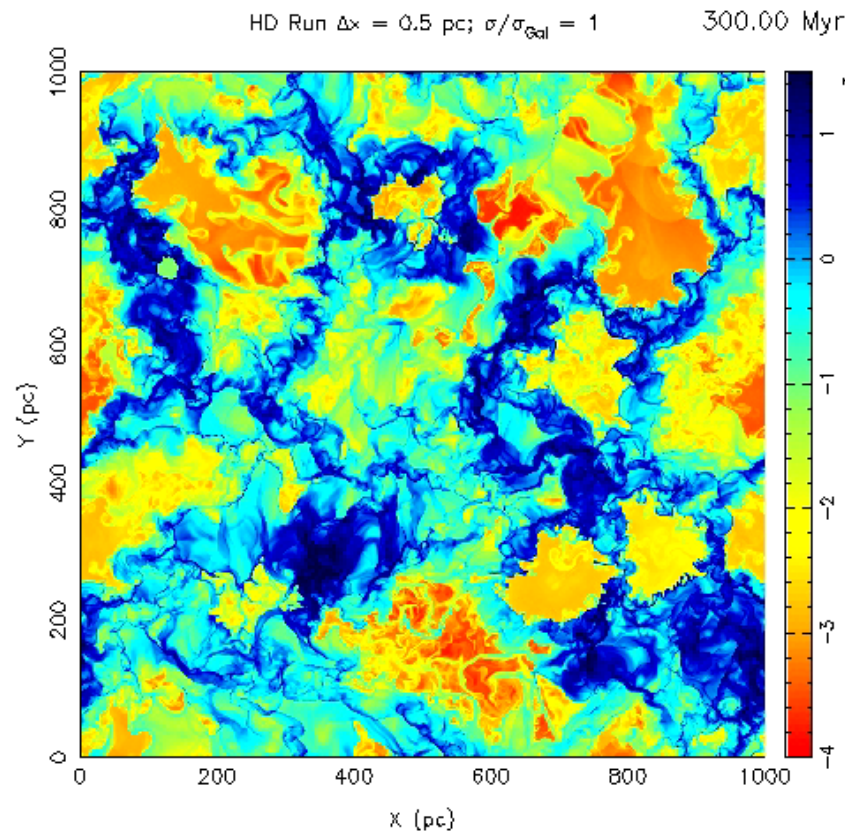
- Star Formation in Spiral Arms
- Galactic Structure
- Numerical Simulations of ISM (MHD 3D)



# Assist the Interpretation of Ejecta Kinematics in the Galaxy

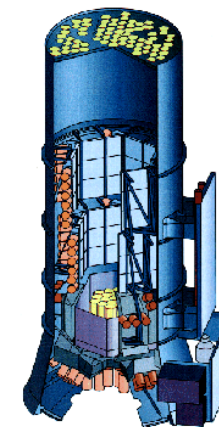
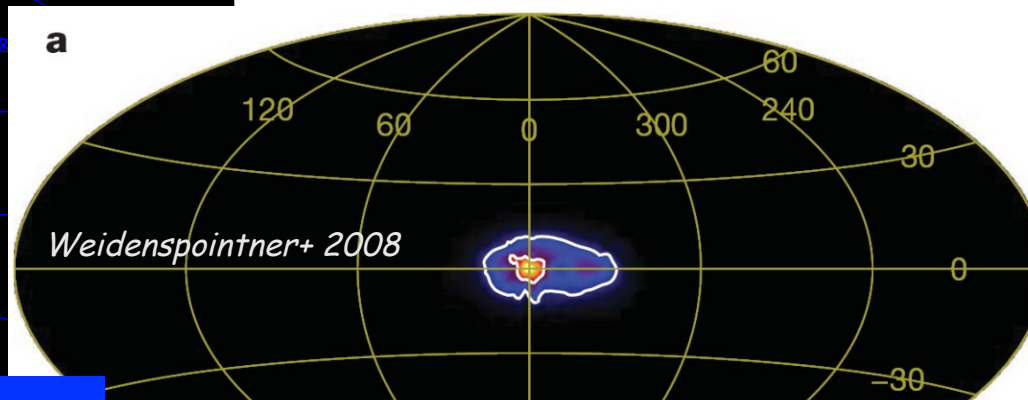
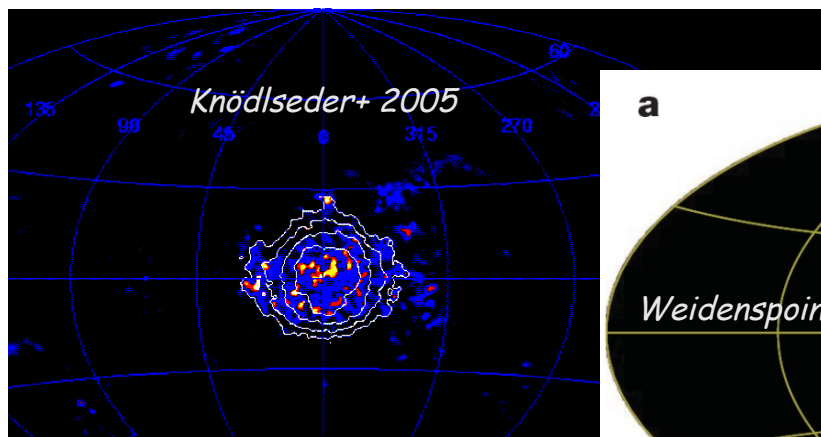


- Stellar Evolution Symmetric around Spiral Arms??

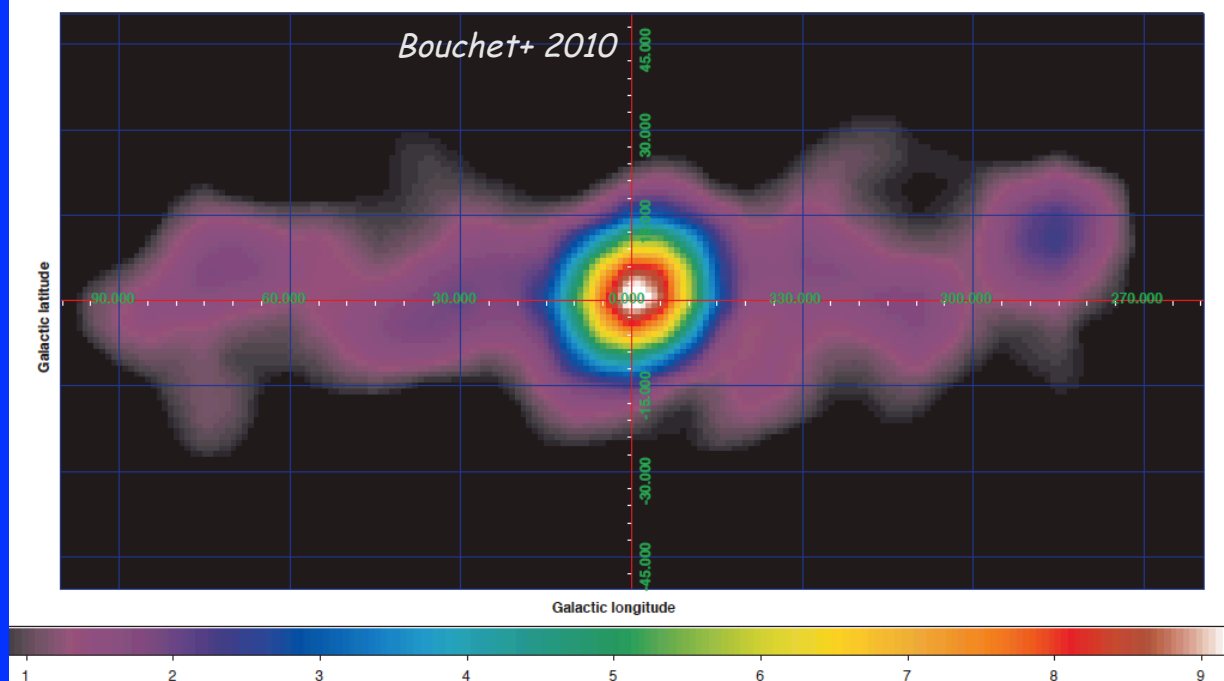


**... annihilation of positrons ...**

# Measuring Galactic Positron Annihilation with SPI



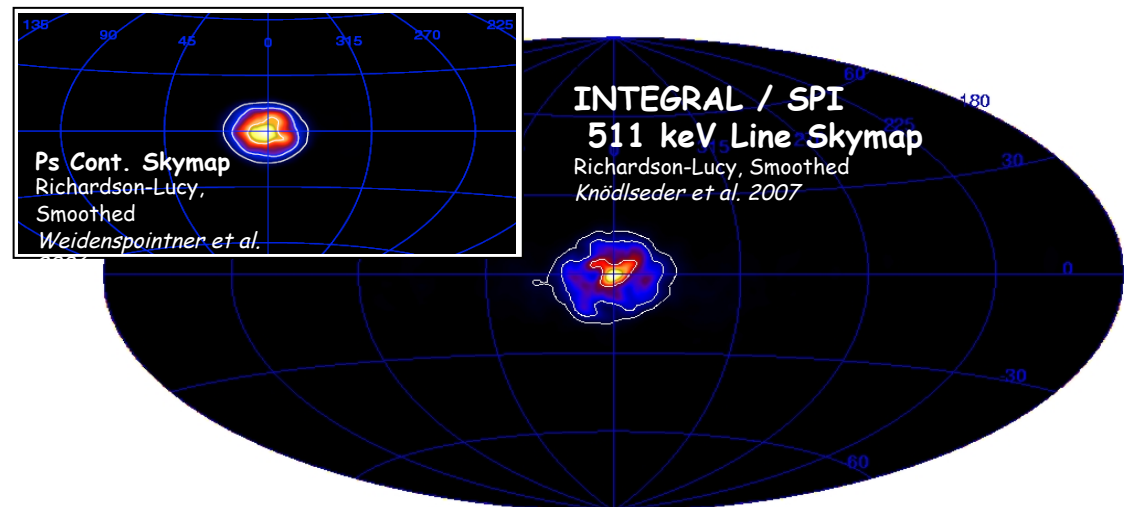
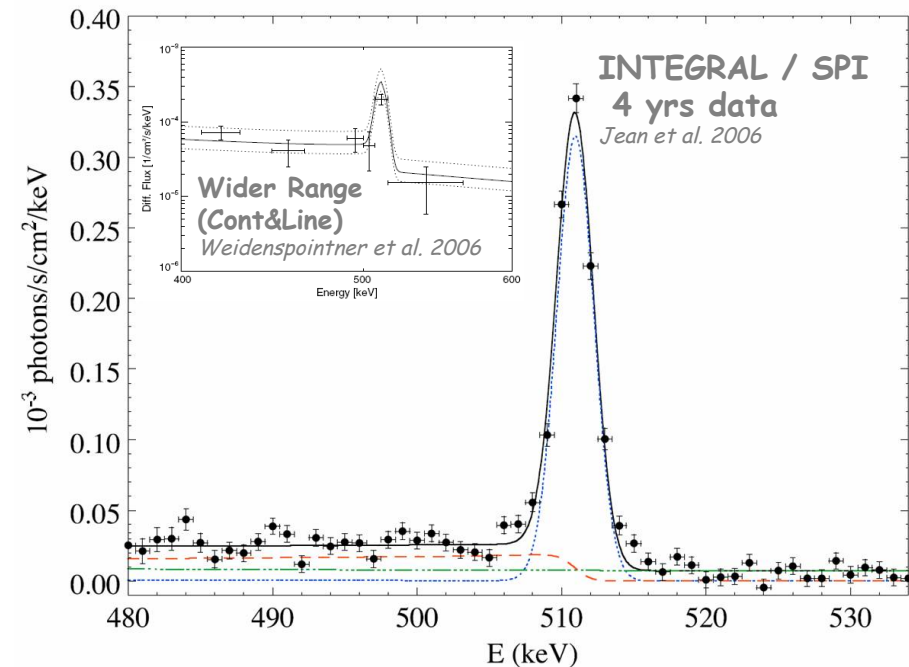
- ☆ Annihilation g-rays are dominated by a Bright Inner-Galaxy Component
- ☆ The  $^{26}\text{Al}$   $e^+$  Produced in the Disk (82%) are a Minor Contribution
- ☆ Annihilation g-ray Emission Presents a Puzzle:
  - ☞  $e^+$  Sources ?
  - ☞ Propagation !!
  - ☞ Annihilation





## INTEGRAL / SPI:

- Extended Emission ( $\sim 8-10^\circ$ ) at  $1.01 (\pm 0.02) 10^{-3} \text{ ph cm}^{-2} \text{ s}^{-1}$
- Ps Continuum:  
 $4.3 (\pm 0.3) 10^{-3} \text{ ph cm}^{-2} \text{ s}^{-1}$   
 $f_{\text{Ps}} 0.967 \pm 0.022$
- Corresponds to  $\sim 2 \cdot 10^{43} \text{ e}^+ \text{ s}^{-1}$
- Line Slightly Broadened



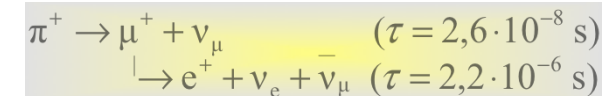
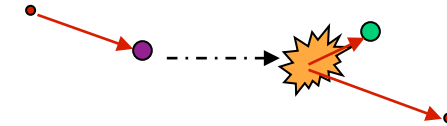
# Positron Production Processes



## ✓ Cosmic-Ray Nuclear Reactions

☆ e.g.  $^{12}\text{C}(p,pn)^{11}\text{C}(\beta^+)$ , or  $^{16}\text{O}(p,\alpha)^{13}\text{N}(\beta^+)$

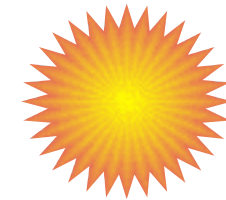
## ☆ Pion Production in HE Collisions



## ✓ Hot-Plasma Pair Production

### ☆ 'kT>MeV'-Plasma

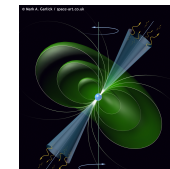
- ☞ Accretion Columns & Disks
- ☞ Jet Bases



## ✓ E.M.-Cascade Pair Production

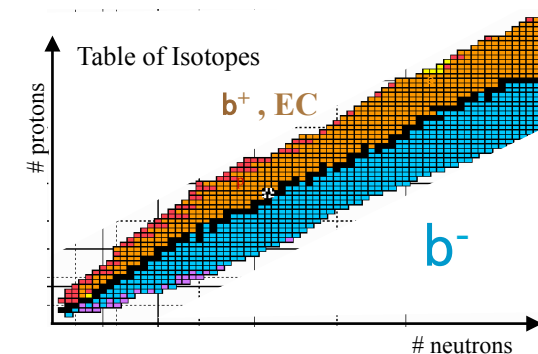
### ☆ Strong Magnetic Fields

- ☞ Pulsars
- ☞ Jets



## ✓ Nucleosynthesis

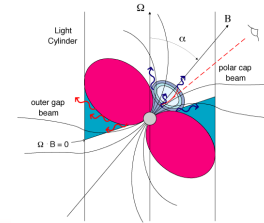
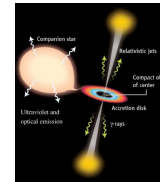
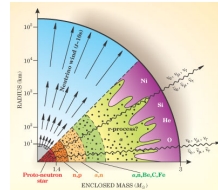
☆ e.g.  $^{56}\text{Ni}(\beta^+)$ ,  $^{44}\text{Ti}(\beta^+)$ ,  $^{26}\text{Al}(\beta^+)$ ,  $^{22}\text{Na}(\beta^+)$ ,  
 $^{13}\text{N}(\beta^+)$ ,  $^{14}\text{O}(\beta^+)$ ,  $^{15}\text{O}(\beta^+)$ ,  $^{18}\text{F}(\beta^+)$



# Candidate Positron Sources



- ★ Nucleosynthesis
- ★ Accreting Binaries
- ★ Pulsars
- ★ SMBH?
- ★ Dark Matter?



Prantzos et al., RMP 83 (2011)

Source	Process	$E(e^+)^a$ (MeV)	$e^+$ rate <sup>b</sup> $\dot{N}_{e^+}(10^{43} \text{ s}^{-1})$	Bulge/disk <sup>c</sup> $B/D$	Comments
Massive stars: $^{26}\text{Al}$	$\beta^+$ decay	$\sim 1$	0.4	$< 0.2$	$\dot{N}$ , $B/D$ : Observationally inferred
Supernovae: $^{24}\text{Ti}$	$\beta^+$ decay	$\sim 1$	0.3	$< 0.2$	$\dot{N}$ : Robust estimate
SN Ia: $^{56}\text{Ni}$	$\beta^+$ decay	$\sim 1$	2	$< 0.5$	Assuming $f_{e^+, \text{esc}} = 0.04$
Novae	$\beta^+$ decay	$\sim 1$	0.02	$< 0.5$	Insufficient $e^+$ production
Hypernovae/GRB: $^{56}\text{Ni}$	$\beta^+$ decay	$\sim 1$	?	$< 0.2$	Improbable in inner MW
Cosmic rays	$p-p$	$\sim 30$	0.1	$< 0.2$	Too high $e^+$ energy
LMXBs	$\gamma-\gamma$	$\sim 1$	2	$< 0.5$	Assuming $L_{e^+} \sim 0.01 L_{\text{obs}, X}$
Microquasars ( $\mu\text{Qs}$ )	$\gamma-\gamma$	$\sim 1$	1	$< 0.5$	$e^+$ load of jets uncertain
Pulsars	$\gamma-\gamma/\gamma-\gamma_B$	$> 30$	0.5	$< 0.2$	Too high $e^+$ energy
ms pulsars	$\gamma-\gamma/\gamma-\gamma_B$	$> 30$	0.15	$< 0.5$	Too high $e^+$ energy
Magnetars	$\gamma-\gamma/\gamma-\gamma_B$	$> 30$	0.16	$< 0.2$	Too high $e^+$ energy
Central black hole	$p-p$	High	?		Too high $e^+$ energy, unless $B > 0.4 \text{ mG}$
	$\gamma-\gamma$	1	?		Requires $e^+$ diffusion to $\sim 1 \text{ kpc}$
Dark matter	Annihilation	1 (?)	?		Requires light scalar particle, cuspy DM profile
	Deexcitation	1	?		Only cuspy DM profiles allowed
	Decay	1	?		Ruled out for all DM profiles
Observational constraints		$< 7$	2	$> 1.4$	

<sup>a</sup>Typical values are given.

<sup>b</sup> $e^+$  rates: in roman: observationally deduced or reasonable estimates; in italic: speculative (and rather close to upper limits).

<sup>c</sup>Sources are simply classified as belonging to either young ( $B/D < 0.2$ ) or old ( $< 0.5$ ) stellar populations.



Only Gamma Rays Can Tell

# Known Sources of Positrons, $E_{e^+}$

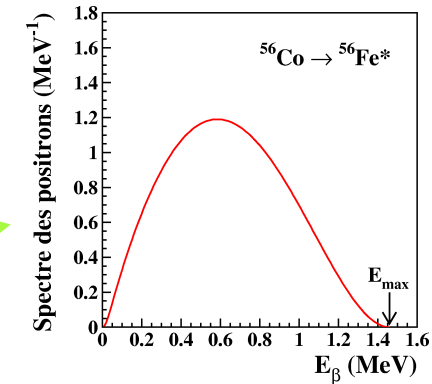


- Radioactive Nuclei

- ★ Sources:

Supernovae, Novae,  
Cosmic Rays & ISM  
~MeV

- ★ Positron Energies:



- Pion Production

- ★ Sources:

Cosmic Rays & ISM

- ★ Positron Energies:

$\langle E \rangle \sim 30$  MeV (MeV...GeV)

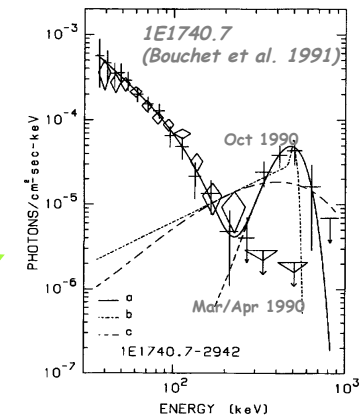
- Pairs from Hot Plasma

- ★ Sources:

Accreting Binaries

- ★ Positron Energies:

~MeV  $T > 100$  keV ( $E_{thr} = 1.02$  MeV)



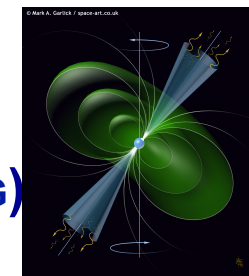
- Pairs from Strong Magnetic Fields

- ★ Sources:

Pulsars, Magnetars

- ★ Positron Energies:

~MeV...GeV ( $E_{thr} = 1.02$  MeV  $B > 10^{12}$  G)

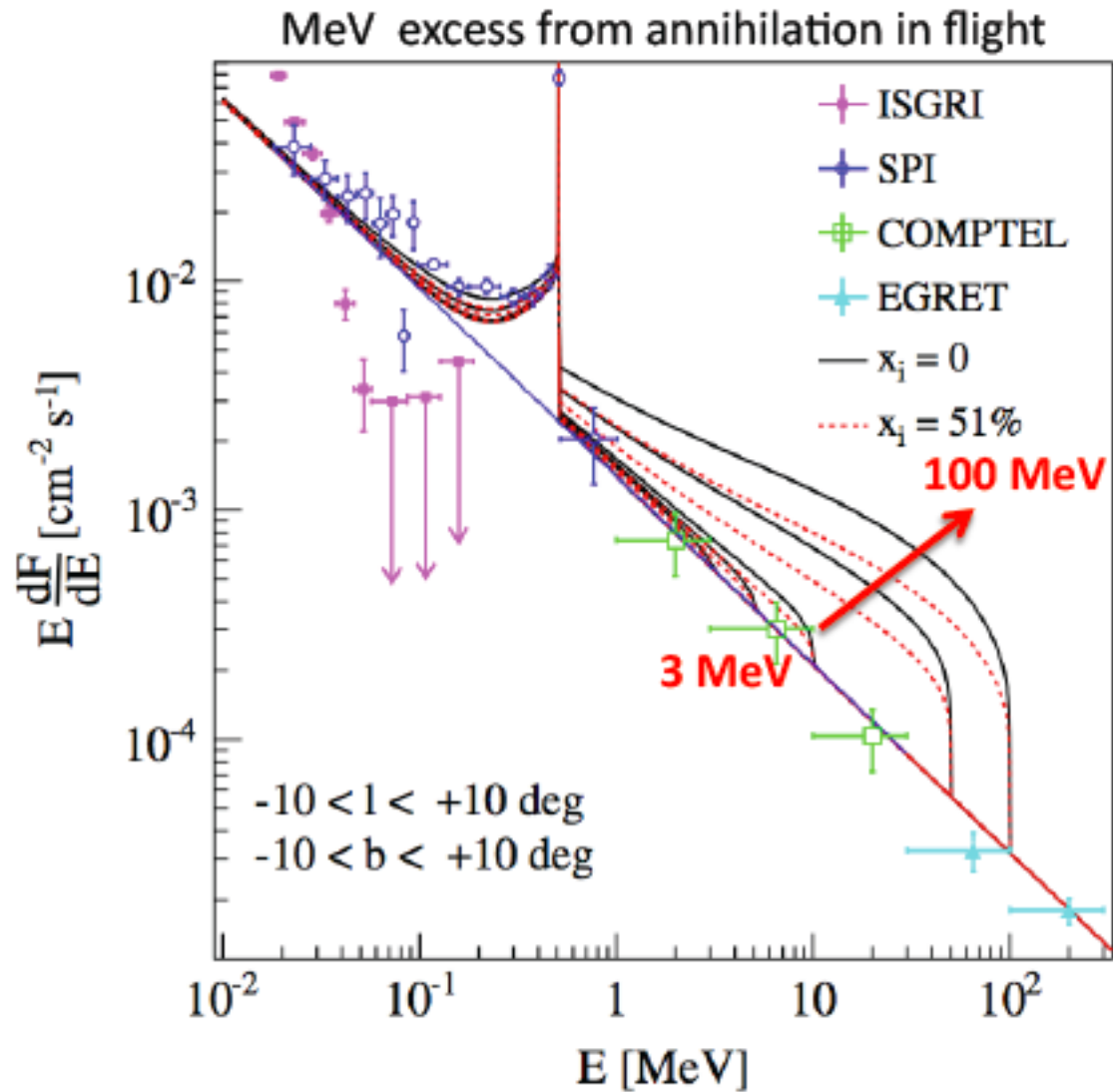




# Annihilation at relativistic energies?



- No



*Sizun et al., (2006)*

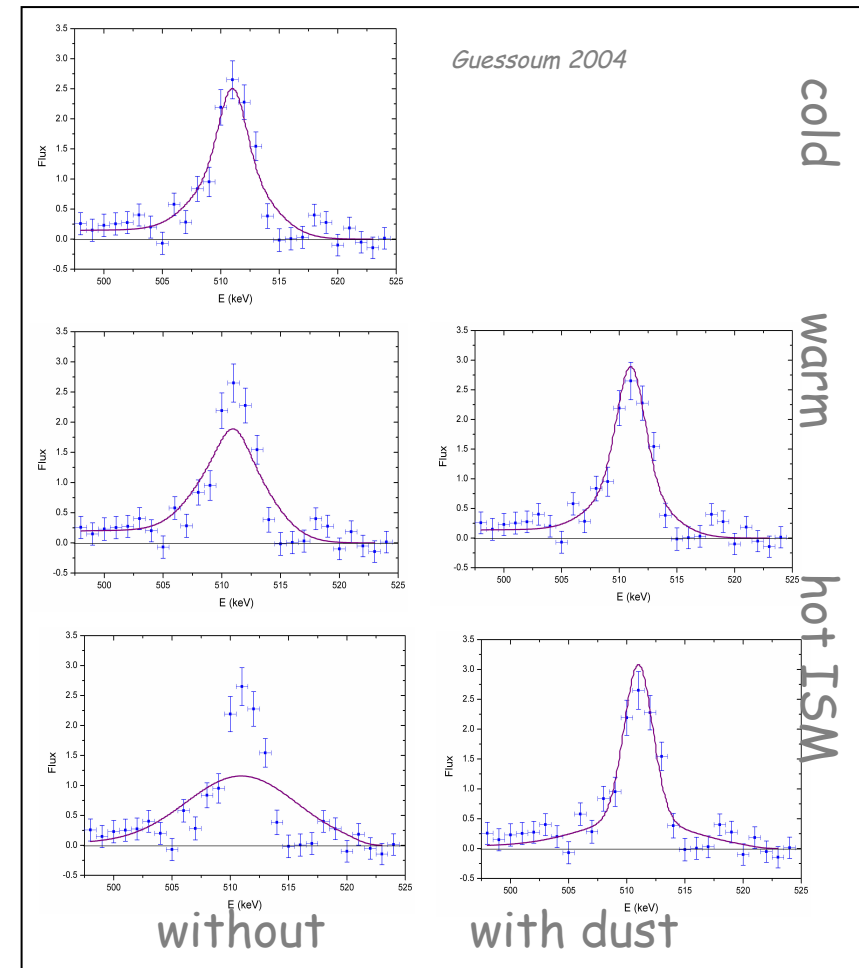
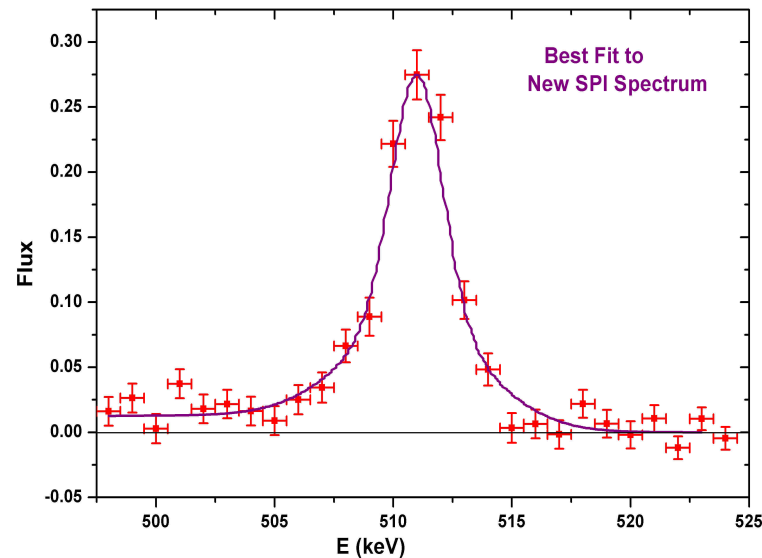
# Annihilation Conditions: Which ISM Phase



## ★ Diversity of Annihilation Processes:

- Direct Annihilation with Free or Bound e-
- Formation of a Positronium Atom
- At MeV Energies
- After Slowing Down
- On Surfaces of Dust

👉 Momentum Balance  $\leftrightarrow$  Line Width



## Annihilation Conditions: Which ISM Phase?

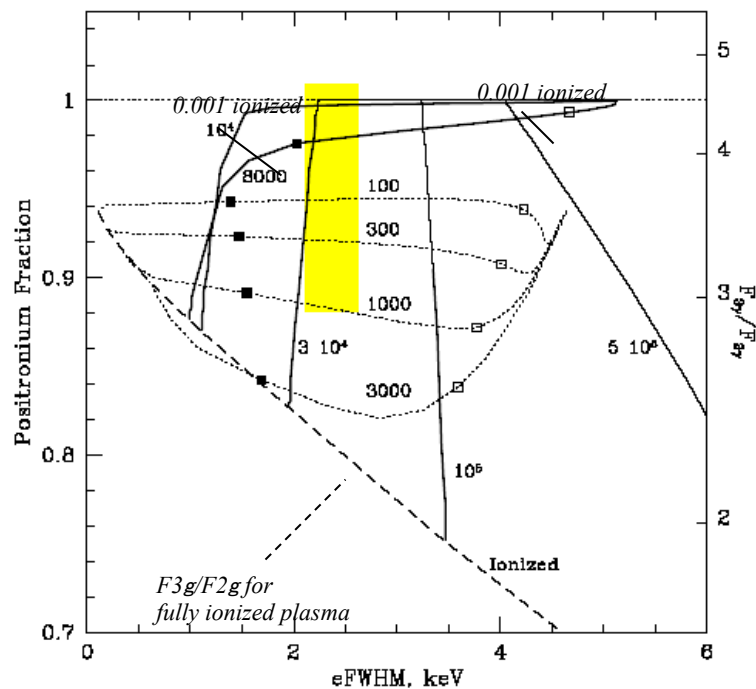
- ★ Warm Ionized ISM is Dominating Annihilation Environment
- ★ No ISM Grain “Narrowing” Needed

👉 Jean et al. 2005, 2006

- Fitting Different Phases with their Characteristic Spectral Shapes

👉 Churazov et al. 2004

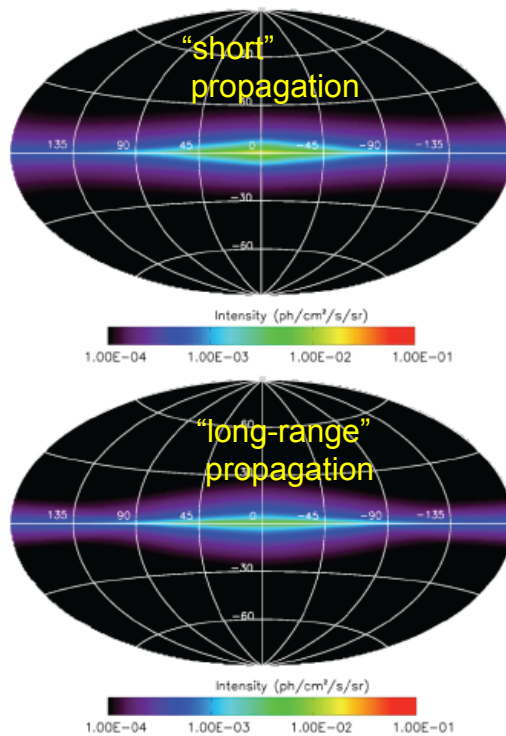
- Determining the best-matching Temperature and Ionization Fraction



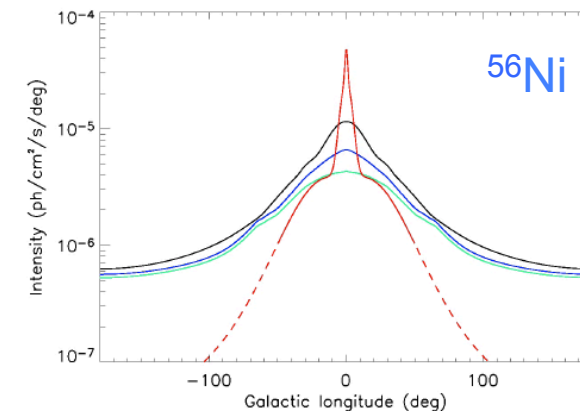
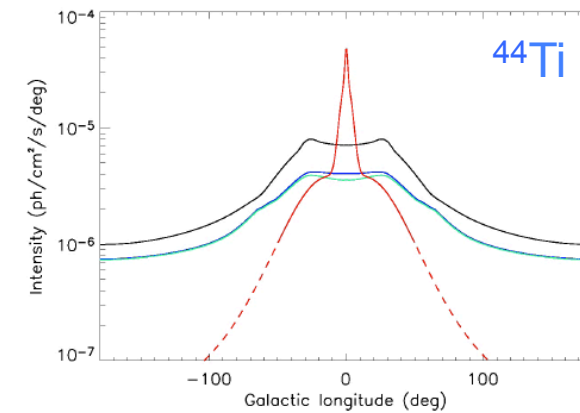
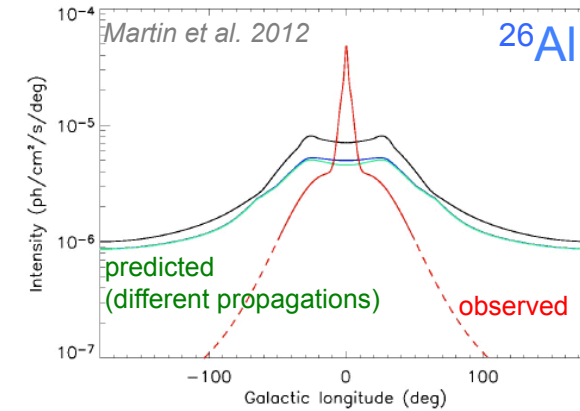
# Morphology of Positron Annihilation Emission



- Nucleosynthesis Explains the Disk Emission



- Another Source Needed for the Bulge





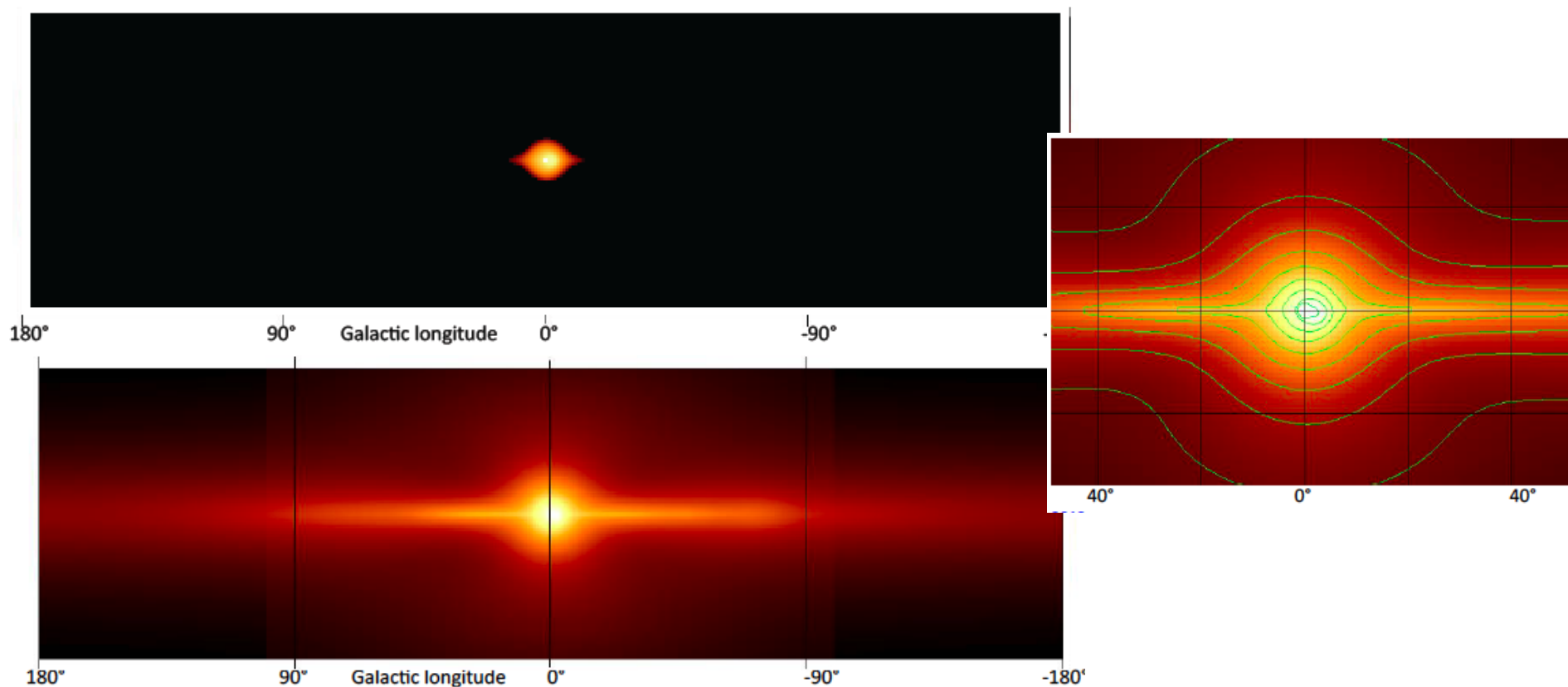
# Remarks on $e^+$ Source Models



- Disk emission is explained by nucleosynthesis
  - ★  $^{26}\text{Al}$  contributes most,  $^{44}\text{Ti}$  and  $^{56}\text{Ni}$  may add
  - ★ all other disk sources may also contribute
  - ★ it is unclear how much of  $e^+$  are lost to halo (chimneys)
  - ★ possibly local variations are plausible, eg from nearby sources such as Sco-Cen or Cygnus; these may confuse by local offsets
- DM is a candidate for the bright bulge emission
  - ★ In the scattering/annihilation ( $\sim r^2$ ) variant, its morphology reproduces a “bulge”
  - ★ The cross section and DM densities remain undetermined by this approach, but estimates lead to plausible parameters
  - ★ Unclear is how the resulting  $e^+$  propagate, as magnetic fields in the inner galaxy are peculiar and strong (arcs), and the profile width may change, plus asymmetries in propagation may modify it

# Imaging the 511 keV Line Emission

- ☆ Using 10 y of data, bgd model from ACS tracers etc  
👉 **Skinner et al. 2013**
- ☆ Sky image dominated by “bulge” component
- ☆ Weak (but detectable) emission from the disk of the Galaxy
- ☆ Central “bulge” is multi-component, not “symmetric”



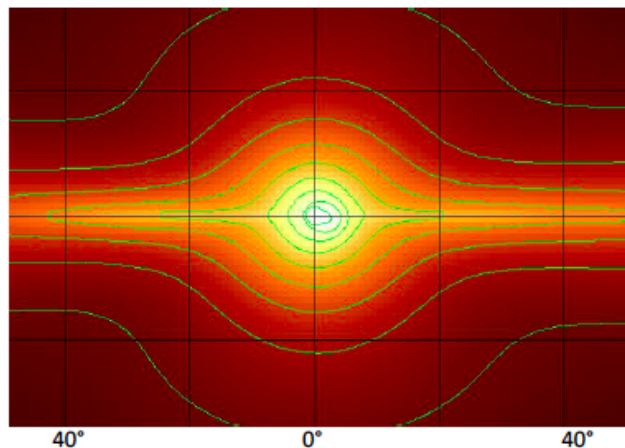
# Understanding the 511 keV Line Emission

## ☆ After 10 y of measurements and various different analyses

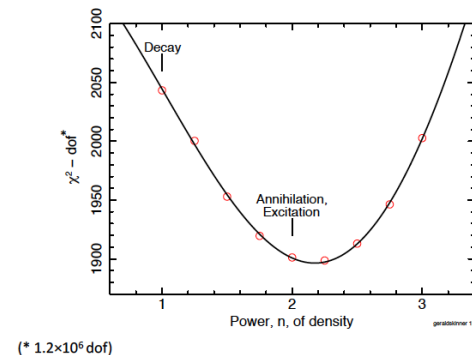
☞ Knödlseeder+ 2005, Jean+ 2005, Weidenspointner+ 2008, Churazov+ 2011, Bouchet+ 2011, Skinner et al. 2013

## ☆ Surprisingly-bright extended “bulge-like” emission

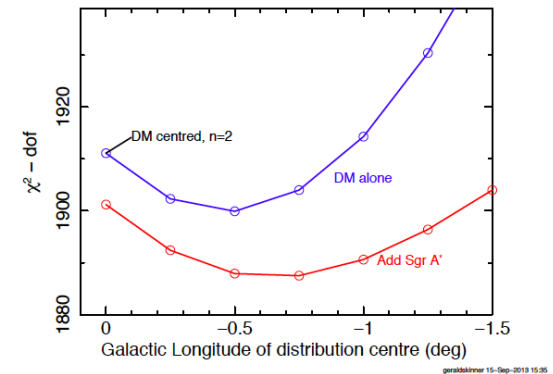
- ☞ None of the plausible candidate sources would produce this
- ☞ The centroid appears offset by  $\sim 1$  deg towards 4<sup>th</sup> quadrant
- ☞ Sgr A\*(?) appears to contribute ‘point-like’ emission, but cannot explain the extended bulge
- ☞ Dark matter (annihilation, not decay) matches the observed morphology



Fitting a model with a disk from radio-active decay plus a bulge core with  $F \propto (\rho_{DM})^n$  and  $\rho_{DM}$  based on an NFW dark matter profile



"INTEGRAL's journey through the high energy sky" Rome, Oct 15-18 2013



## ☆ ~Expected emission from the disk of the Galaxy (<sup>26</sup>Al, etc.)

- ☞ Many plausible candidate sources compatible with observations
  - Pulsars, microquasars, supernovae and novae, ...

# Galactic Positron Annihilation: Summary



★ **Annihilation g-Rays are a New Astronomical Domain / Window**

★ **Galactic-Disk Emission: More-than-enough Sources, probably Nucleosynthesis; Bulge Emission: a Puzzle**

★ **Positron Transport and Annihilation Environment Diagnostics → Cosmic-Ray and ISM Astrophysics**

★ **Spatial Profile of Annihilation Emission → Discriminate Candidate Sources**

- 👉 **Disk versus Bulge Sources**
- 👉 **Galaxy Survey**
- 👉 **Deep Exposures are Needed to Constrain Contributions of Specific Source Types (Individual, Groups)**
- 👉 **SPI++, and Next-Generation Instruments**

